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NAVY VEHICLE DESIGN AND CONSTRUCTION: MEASUREMENT OF TRIAXIAL VIBRATION AT SIGNIFICANT HUMAN INTERFACE POINTS ON THE CH-47C AND SH-3A HELICOPTERS

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Prepared by

C.W. Hutchins

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13. ABSTRACT

Triaxial vibration levels were recorded on the CH-47C and SH-3A helicopters at the pilot's seat, collective control stick, rudder pedal, instrument panel, and the pilot's head (Z-axis only). These recordings were made on two separate two-hour flights for both helicopters. The first flight was a continuous mission profile representative of the helicopters' primary mission. The second flight consisted of discrete maneuvers representative of a broad scope of mission profiles. The resulting vibration tapes were subjected to specturm analysis and three peak frequencies found. These peaks were seen to be a function of the rotor head frequency and two harmonics of this frequency. Each of the three peak frequencies was shown to be critical in terms of human performance parameters.

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FOREWORD

This report presents work which was performed under the Joint Army-Navy Aircraft Instrumentation Research (JANAIR) Program, a research and exploratory development program directed by the Department of the Navy, Office of Naval Research. Special guidance is provided to the program for the Army Electronics Command, the Naval Air Systems Command, and the Office of Naval Research through an organization known as the JANAIR Working Group. The Working Group is currently composed of representatives from the following offices:

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Department of the Army
Army Electronics Command, Avionics Laboratory
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[Instrumentation Technical Area (AMSEL-VL-1)]

The Joint Army-Navy Aircraft Instrumentation Research Program objective is to conduct applied research using analytical and experimental investigations for identifying, defining, and validating advanced concepts which may be applied to future, improved Navy and Army aircraft instrumentation systems. This includes sensing elements, data processors, displays controls, and man/machine interfaces for fixed- and rotary-wing aircraft for all flight regimes.

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1.0 Introduction

1.1 Purpose and Scope

The projected increase in the utilization of helicopters as a weapons delivery and sensor platform necessitates an increased awareness of man's performance capabilities in this dynamic environment. This environment includes acceleration, vibration, noise and temperature as principal parameters effecting human performance. Of these, vibration has been found to have the greatest impact on human performance. While much research has been devoted to the effects of vibration on human performance, the complexity of this parameter makes straightforward projection to the helicopter environment tenuous at best.

In view of this situation the JANAIR (Joint Army Navy Aircraft Instrumentation Research) Group decided to measure inflight vibration at all significant human interface points for a cross-section of Army and Navy operational helicopters. This vibration was to be collected in all three axes of motion: X-axis (transverse), Y-axis (lateral), and Z-axis (vertical). It was further decided that two data tapes should be recorded for each helicopter, one a primary mission profile continuously recorded from take-off to touch-down, the other a component tape consisting of discrete maneuvers representative of a broad scope of primary and secondary missions. These tapes would serve two main purposes:

(1) Provide much needed data relevant to the helicopter vibration environment.

(2) Provide magnetic tape recordings for use in dynamic simulation of this environment.

The present study is a first step toward fulfilling these goals.

Two helicopters were selected for initial investigation; the CH-47C, the Army's medium transport/aircraft recovery helicopter and the SH-3A, the Navy's ASW (Anti-submarine warfare) helicopter. Triaxial vibration levels were recorded on both helicopters at the rudder pedal, collective control stick (referred to as the thrust lever on the CH-47C), instrument panel, pilot's seat, and pilot's head (vertical axis-only). An additional recording was made at the sonar operator's seat in the SH-3A and the left side of the instrument panel in the CH-47C. These vibration measurements were simultaneously recorded on magnetic tape on two separate flights for each helicopter - a two-hour primary mission profile from take-off to touch-down and a discrete component flight

consisting of those maneuvers representative of a broad spectrum of missions performed by these helicopters. The primary mission profile chosen for the CH-47C was a helicopter recovery mission The SH-3A mission selected was an ASW sonar search mission. The main purpose for the component tape was to provide a means of constructing desired mission profiles for future simulation efforts by selecting relevant maneuvers and splicing them into a continuous profile tape. This tape was used for the specturm analysis since it provided superior control of each maneuver segment as well as a longer time record for each maneuver.

In recording inflight vibration, major emphasis was placed in the low frequency portion of the spectrum (1-30 Hz); as this region contains primary and secondary whole body resonance and the vast majority of individual organ resonating frequencies. In addition, below 2 Hz the body moves as a simple mass with little relative internal motion and above 30 Hz any vibratory energy transmitted to the body is absorbed at the point of contact, thus minimally affecting performance.

1.2 Background

Research into the effects of vibration on human performance has been voluminous, however, the vast majority of studies have utilized vertical sinusoidal vibration. Very little research has involved triaxial random vibration similar to that found in the helicopter environment. The complexity of this area of research makes comparisons between studies extremely tenuous. In order to adequately compare two studies the following parameters must be specified: frequency, amplitude, direction, and duration of the vibration; orientation of the subject, peak as well as rms-g levels involved, vibration levels at all human interface points, type and location of all restraints, waveform of the vibration at its source and at the subject, and levels of other environmental parameters present.

While the majority of research is not directly applicable to the helicopter environment, it does provide some indication of the anticipated effects of this environment on the human operator's performance.

1.2.1 Visual Performance

Grether (1971) pointed out that under vibration the visual image is blurred causing a decrement in visual acuity. This decrement also is a function of impairment in maintaining the accommodation and fixation essential for optimal visual acuity. In support of this reasoning, Mozell and White (1958) found vibration above 8 Hz had a detrimental effect on the ability to read digits on airplane instruments. The frequency range having the greatest effect on visual acuity was found to be 10-25 Hz (Lange and Coermann, 1962; O'Briant and Ohlbaum, 1970). This

decrement in visual acuity is not however a simple function of relative displacement of subject and target. Guignard and Irving (1962) discovered that the response of the pursuit movements made by still subjects fixating on oscillating targets was lower than the frequency response of compensatory eye movements fixating a static target during vibration of the man. This phenomenon was found to be frequency dependent by Dennis (1965), who found that at 6 Hz, vibration of the visual object resulted in higher impairment of vision than comparable vibration of the human, however at 14, 19 and 27 Hz the reverse was found to be the case. Lange and Coermann(1962) divide the effects of vibration on visual acuity into two parts: below 12 Hz this impairment is accounted for by the physiological stress; above 12 Hz it is due to image displacement on the retina. Guignard and Irving (1960) found that scanning performance was significantly impaired by vibration in the 1-9 Hz range. They found the greatest impairment in scanning performance to occur at 3.4 Hz. To further complicate matters Ohlbaum et al.(1971) found that this effect of vibration on visual acuity was dependent on viewing distance. With g-load held constant, at .4 M, visual impairment increased as frequency decreased, at 1.0 M the relationship was rather flat, while at 4.0 M impairment significantly decreased as frequency decreased.

1.2.2 Auditory Performance

Teare (1963) found that auditory threshold increased with vibration in the 1-27 Hz range. In the 2-8 Hz range, Teare found that subjects spoke in short bursts. Although the threshold shifts found in this study were not considered to be of practical significance, the combination of noise and vibration found in the helicopter environment may combine to create problems in communication between operators.

1.2.3 Manual Tracking Performance

As would be expected, vibration has been found to have a significant effect on human tracking performance. Buckhout (1964) found a 34-74% decrement in vertical tracking performance and a 10-48% decrement in horizontal tracking performance under vertical vibration. The usual finding is that the decrement in tracking performance is greatest in that axis aligned with the direction of dominant vibration; however, Shoenberger (1970) found that whereas this was true for the vertical axis, horizontal vibration had a greater effect on vertical tracking than did vibration in the vertical axis. Forbes (1959) attributes the effects of vibration on tracking performance to shoulder-girdle resonance, degraded visual acuity of the target, as well as the jolting of the subject's arm and hand during vibration.

1.2.4 Central Neural Processes

The vast amount of research has found little effect of vibration on the central neural processes; however, Shoenberger (1970) found decrements in choice reaction time under vibration at the 1-11 Hz range. Poorer vigilance performance under vibration was found by Hornick and Lefritz (1966), and Shoenberger (1969). Harris and Sommer (1971) found that high intensity noise and vibration combine to produce a decrement in mental subtraction ability. This effect was greater at 5 Hz than at 3 or 12 Hz. Hutchins (1970) found that vibration increased the reaction time and false alarm rate of subjects responding to simulated MAD (Magnetic Anomaly Detection) signals. Buckhout (1964) found that low frequency vibration increased the incidence of procedural errors (hitting wrong switch).

1.2.5 Fatigue and Discomfort

While this area is more difficult to define precisely, it has an obvious relationship to human performance and crew morale. Chaney (1965) reported that low frequency vibration (1-12 Hz) resulted in subjective reports of itching, flapping of skin, mild pain, perceived tightness, swallowing difficulty and dizziness. Beaupeurt et al. (1969) report that in the 1-4 Hz range low back pain is a fairly common complaint of subjects. Gaeuman et al. (1962) found increased oxygen consumption attributable to vibration. They attributed this increased oxygen consumption to voluntary and involuntary muscular guarding in an attempt to dampen the vibration, resulting in an increase in body metabolic activity. Over time this increased metabolic activity leads to muscle fatigue. Guignard and Travers (1959) found that when the whole body or a single limb was vibrated at low frequencies, bursts of action potentials synchronous with the stimulus were present from a muscle in that limb. They concluded that low frequency vibration elicits a periodic synchronous stretch reflex from resting postural muscles. Hoover and Ashe (1962) found evidence of hyperventilation caused by vibration, especially at 6 Hz, due to the resonance of the abdominal organ mass at this frequency. Gaeuman et al. (1962) also found a sedative effect at 2 Hz. Guignard and Travers (1960) reported instances of disturbances in equilibrium and difficulty in maintaining normal body posture. This constant effort to maintain posture under vibration results in an expenditure of energy and contributes to fatigue.

1.2.6 Miscellaneous Effects

Vogt, et al, (1968) and Vykukal (1968) measured the mechanical impedance of the human body under various levels of sustained acceleration and found that the frequency at which the body resonates increases with increased levels of sustained acceleration. As sustained acceleration increases, the body stiffens with a resultant reduction in its damping capability. This process results in a higher

energy transmission between the vibration source and the internal organs and head. Hornick (1962a) found that within two minutes the human leg gradually loses its ability to isolate vibration, thus increasing intensities of motion are transmitted to the body. Hornick (1962b) found that vibration caused a decrement in the subjects' ability to maintain foot-pressure. Streeter (1970) found a loss in sensitivity in the hand as the result of vibration in the 30-480 Hz area. He attributed this to the tendency of the body to absorb the vibration energy at the point of contact at these frequencies; below 30 Hz the energy is transmitted from the point of contact to the internal organs and head.

1.2.7 Helicopter Environment

Dean et al. (1964) measured the vibration and noise levels in the CH-46A and found the vibration wave form to be complex with discrete superimposed sinusoidal frequencies. The major peaks occurred at frequencies corresponding to the rotor head rate (known as the 1/rev frequency), the blade rate (known as the n/rev frequency) and harmonics of the 1/rev frequency. The 1/rev frequency for the CH-46A was 4 Hz while the n/rev frequency was 27 Hz. Overall rms-g levels varied from .195 in hover to .410 in rapid descent, with the frequency pattern peaking at 1/rev, n/rev and harmonics thereof throughout the manuvers examined. The main power was found at the n/rev frequency. In some instances the rms-g levels recorded at this frequency were found to exceed MIL-H-8501A. The second most predominant frequency was 1/rev, with the 2/rev frequency also exhibiting peak power. The higher order harmonics exhibited decreasing power, especially at the pilot's head. During relatively low intensity vibration there was considerable attenuation between the floor and the pilot's head at the higher frequencies; the lower frequencies (1/rev and 2/rev rates) exhibited little attenuation. During high intensity vibration this attenuation was not found. Overall cabin noise levels in the CH-46A varied from 107db at liftoff to 114 db at 130 knot cruise. Ketchel et al. (1969) in a survey of existing helicopters, report 1/rev frequencies ranging from 3-5 Hz and n/rev frequencies ranging from 12-25 Hz. This finding of peak frequencies in the 3-5 Hz area is of particular relevance to human performance, since it is precisely in this range (primary body resonance) where the greatest decrements in most aspects of human performance have been found. This combination of low frequency vibration and high ambient noise levels found in helicopters implies an environment highly suspect in terms of its effect on the human operator. As the scope of the helicopter broadens and man's tasks correspondingly increase in scope and complexity, it becomes increasingly clear that more data relevant to this complex environment is urgently needed.

2.0 Procedures

2.1 Inflight Data Recording System

The inflight data recording system utilized in this study was a self-contained carry-on system. This system consisted of four subsystems.

2.1.1 Hewlett Packard 3960 Instrumentation Tape Recorder

This recorder had four multiplex tape tracks, each capable of recording 13 separate channels of data. The present configuration utilized tracks 1 and 2 for vibration, track 3 for ICS commentary and track 4 for cabin noise recording. Thirteen telemetry voltage controlled oscillators (IRIG bands 1-13 incl.) were used for the two vibration tracks. This recorder is shown in Figure 1.

2.1.2 Auxillary Battery Package

This package contained 50 Eveready CH4T nickel cadmium batteries in a series/parallel arrangement and provided 32 volts over a four hour recording period. In addition, this package contained the electronics for the 26 channel multiplex operation. The battery package is shown in Figure 2.

2.1.3 Accelerometer Packages

These packages contained a combination of Statham A52 and A6 strain gage accelerometers orthogonally arranged to measure the three axes of vibration. Each package contained all necessary signal conditioning electronics for the three accelerometers and eight Mallory Durocell RM-32 mercury batteries to power these electronics. There were five triaxial packages and one specially configured bite bar accelerometer for picking up vibration at the pilot's head. Figures 3 and 4 show the triaxial package and the bite bar respectively. Figures 5-8 show the accelerometer package placements in the CH-47C. Figures 9-13 show these placements for the SH-3A.

2.1.4 Cabin Noise Measurement System

This system consisted of a one inch B and K condensor microphone with a random impedance corrector, a preamplifier to match impedance between the microphone and the rest of the system, and an amplifier to provide gain. The frequency response of the tape recorder was 50 Hz to 16000 Hz. The microphone was located on the overhead between the cockpit and cabin area on both the CH-47C and SH-3A. Figure 14 shows the microphone placement in the CH-47C. Figure 15 is a simplified schematic representation of the entire inflight data recording system.

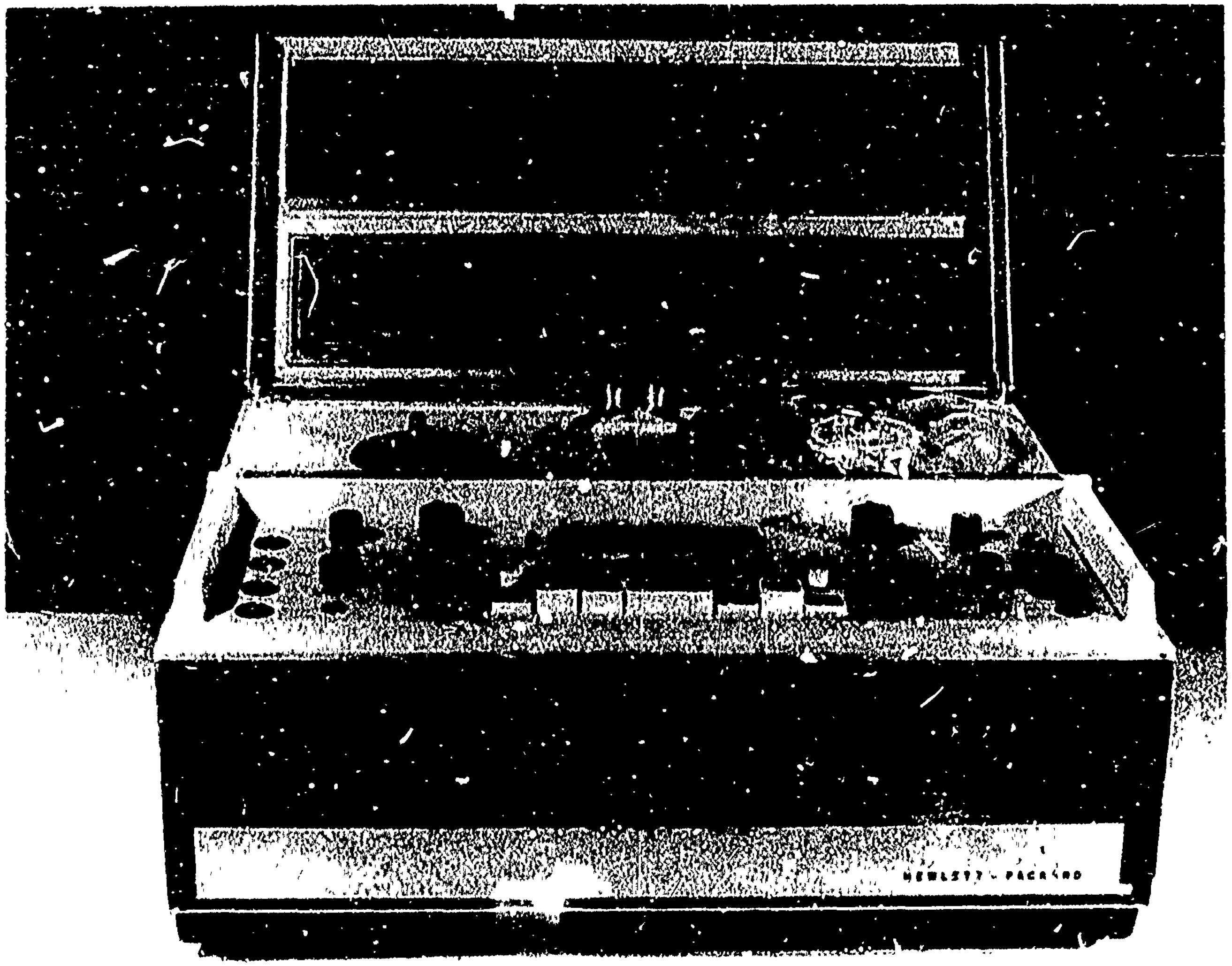

Figure 1. Hewlett Packard 3960 Tape Recorder

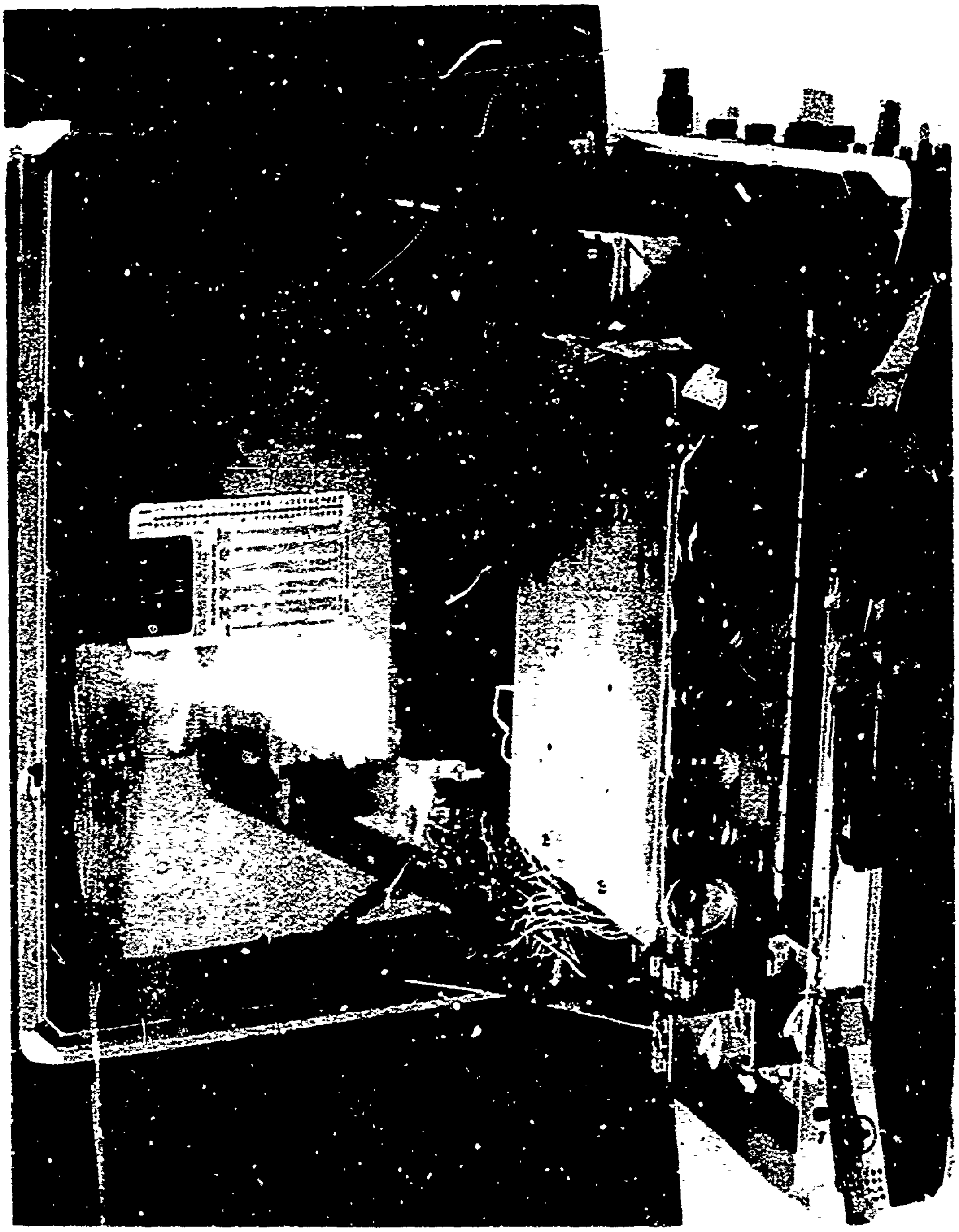

Figure 2. Auxillary Battery Package

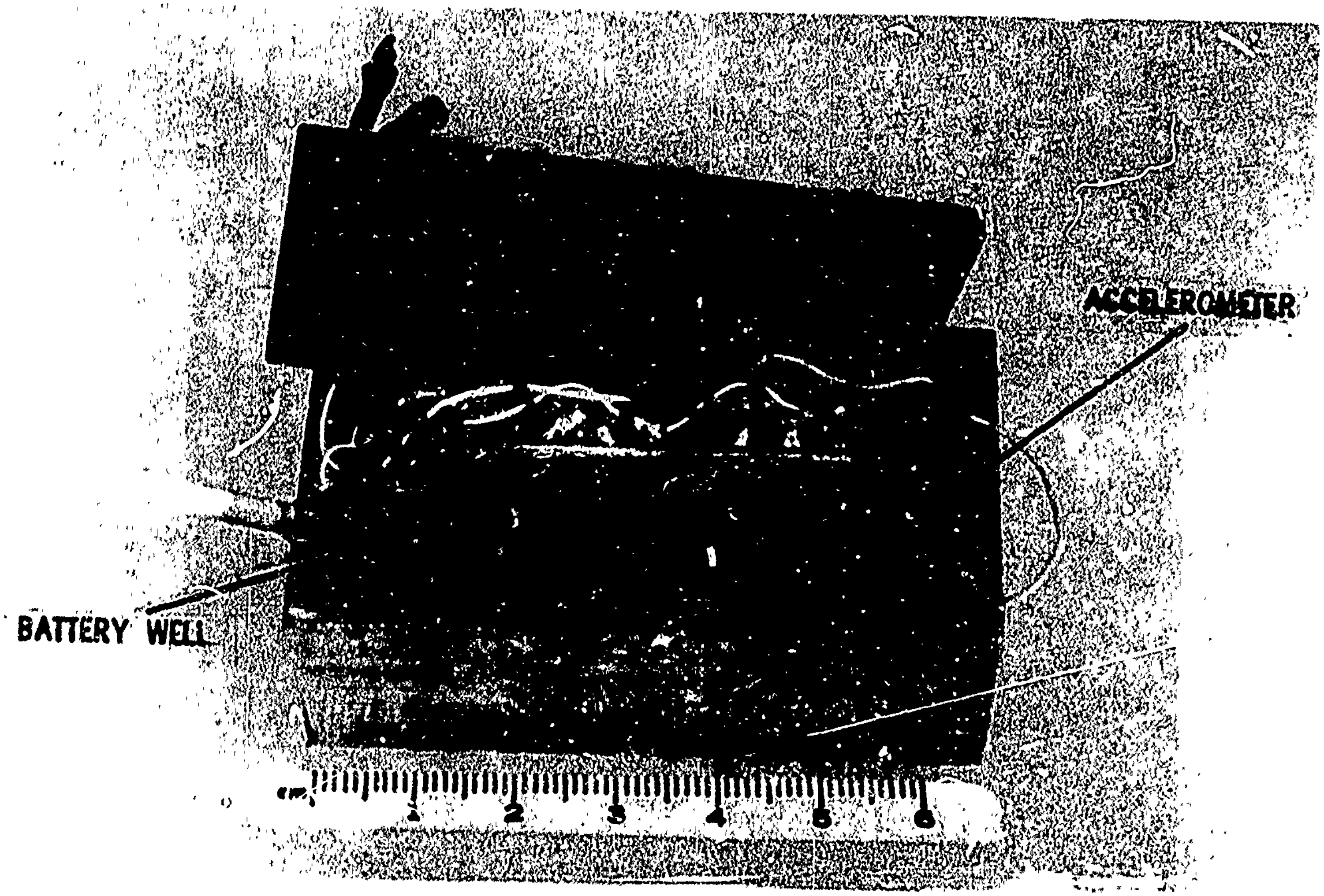

Figure 3. Triaxial Accelerometer Package

Figure 4. Bite-Bar Accelerometer

Figure 5. Position of Rudder Pedal Accelerometer Package in the CH-47C

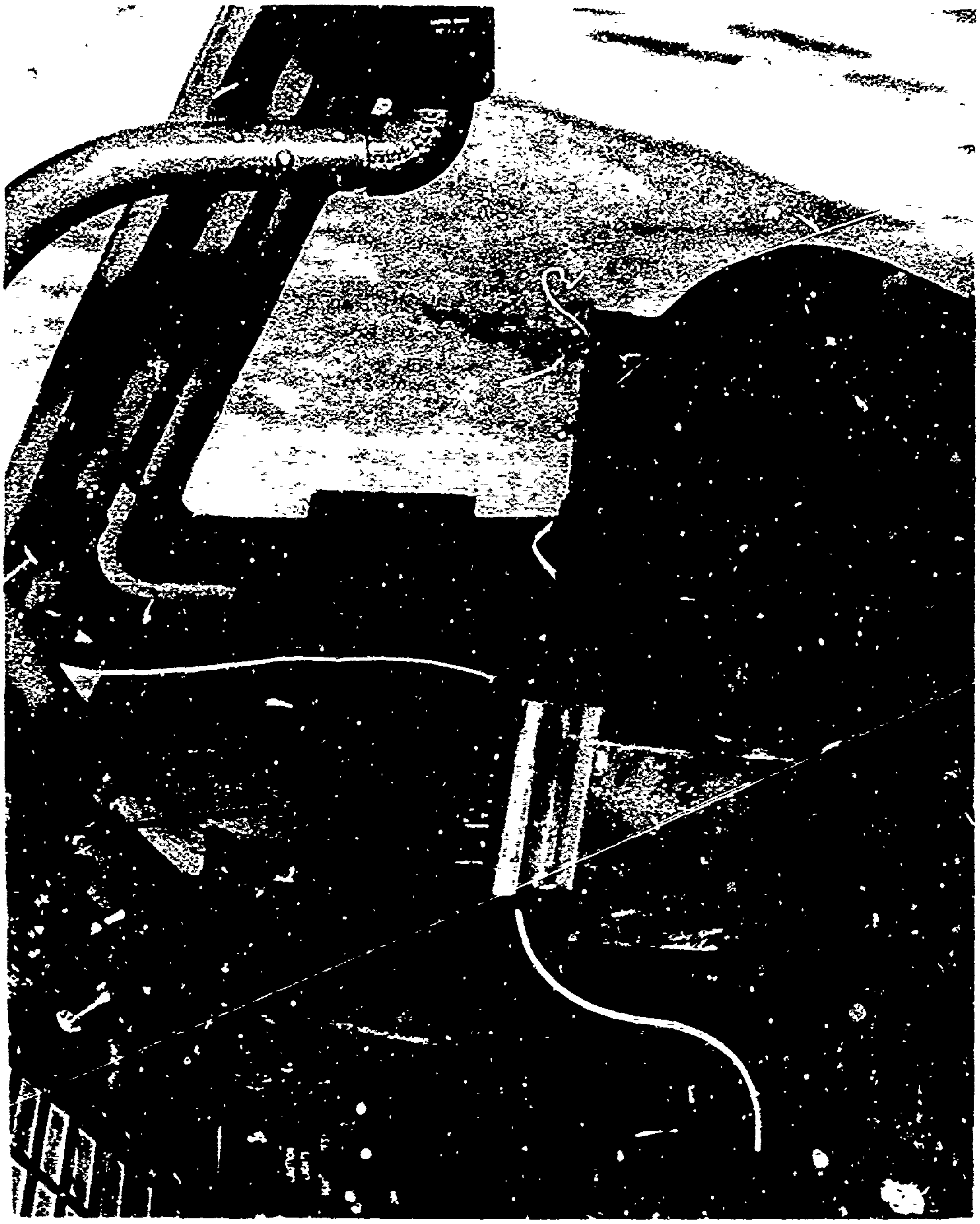

Figure 6. Position of Thrust Lever Accelerometer Package in the CH-47C

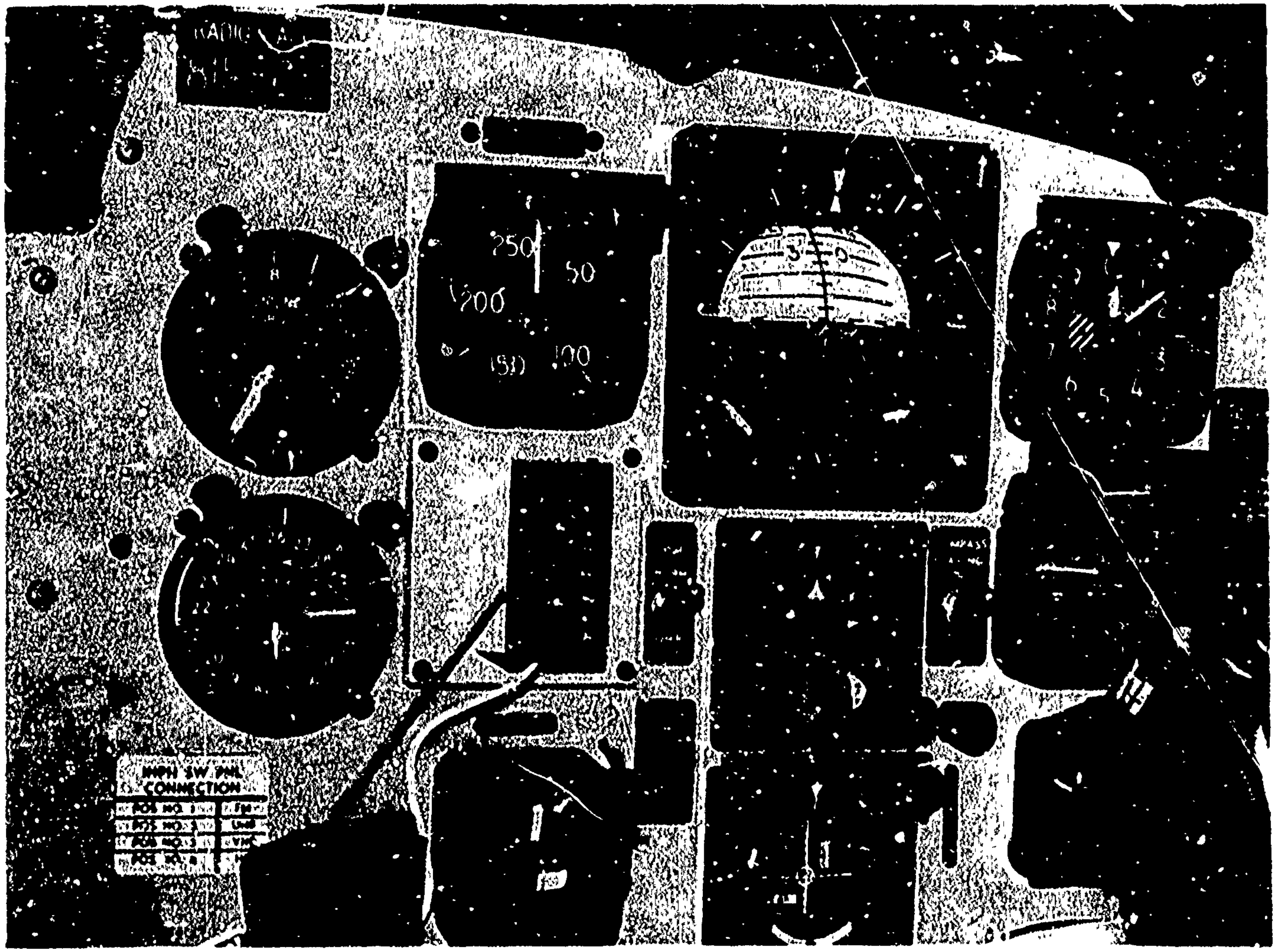

Figure 7. Position of Instrument Panel Accelerometer Package in the CH-47C.

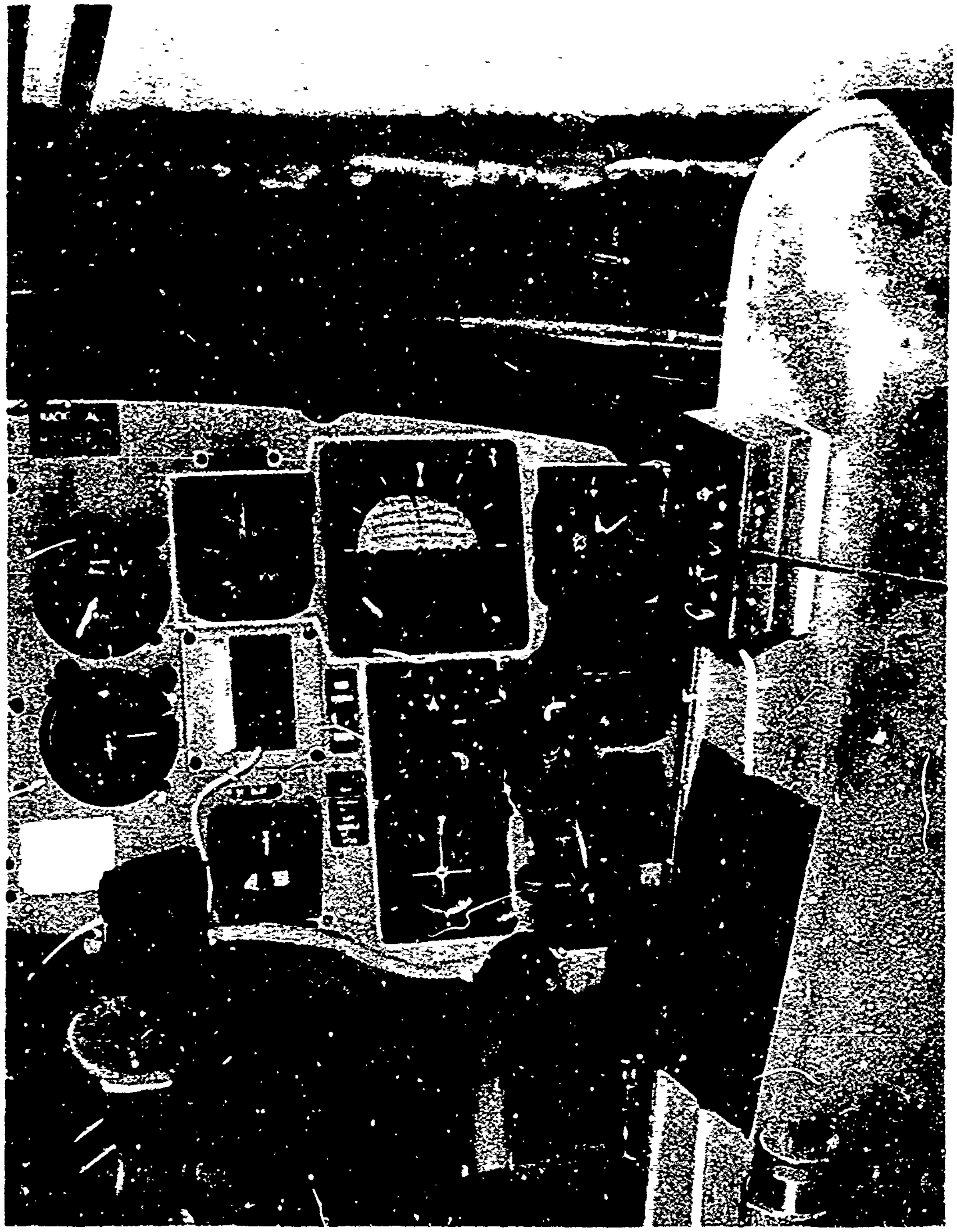

Figure 8. Position of Pilot's Seat Accelerometer Package in the CH-47C

Figure 5. Position of Rudder Pedal Accelerometer Package in the SH-3A

Figure 10. Position of Collective Control Stick Accelerometer Package in the SH-3A

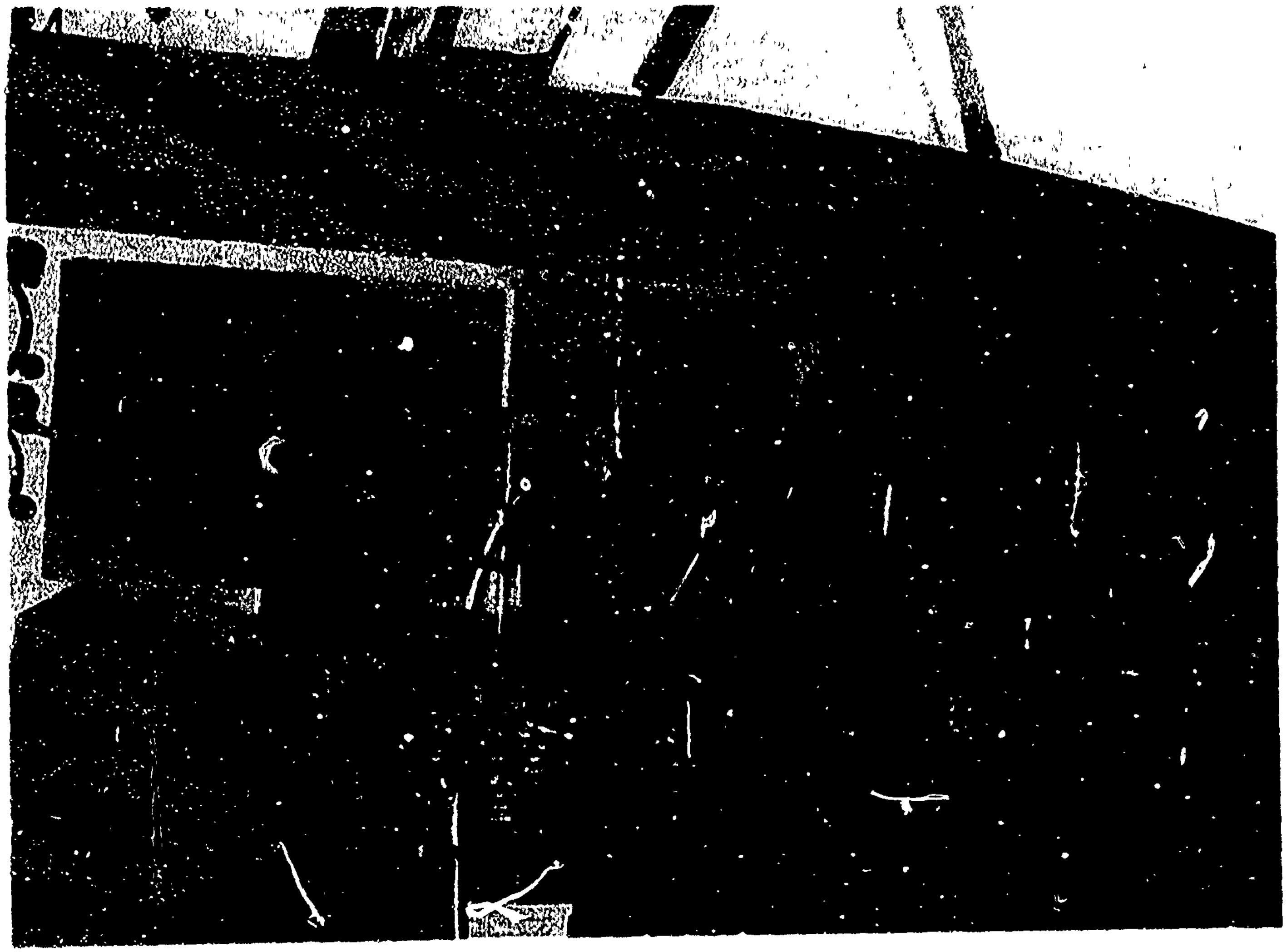

Figure 11. Position of Instrument Panel Accelerometer Package in the SH-3A

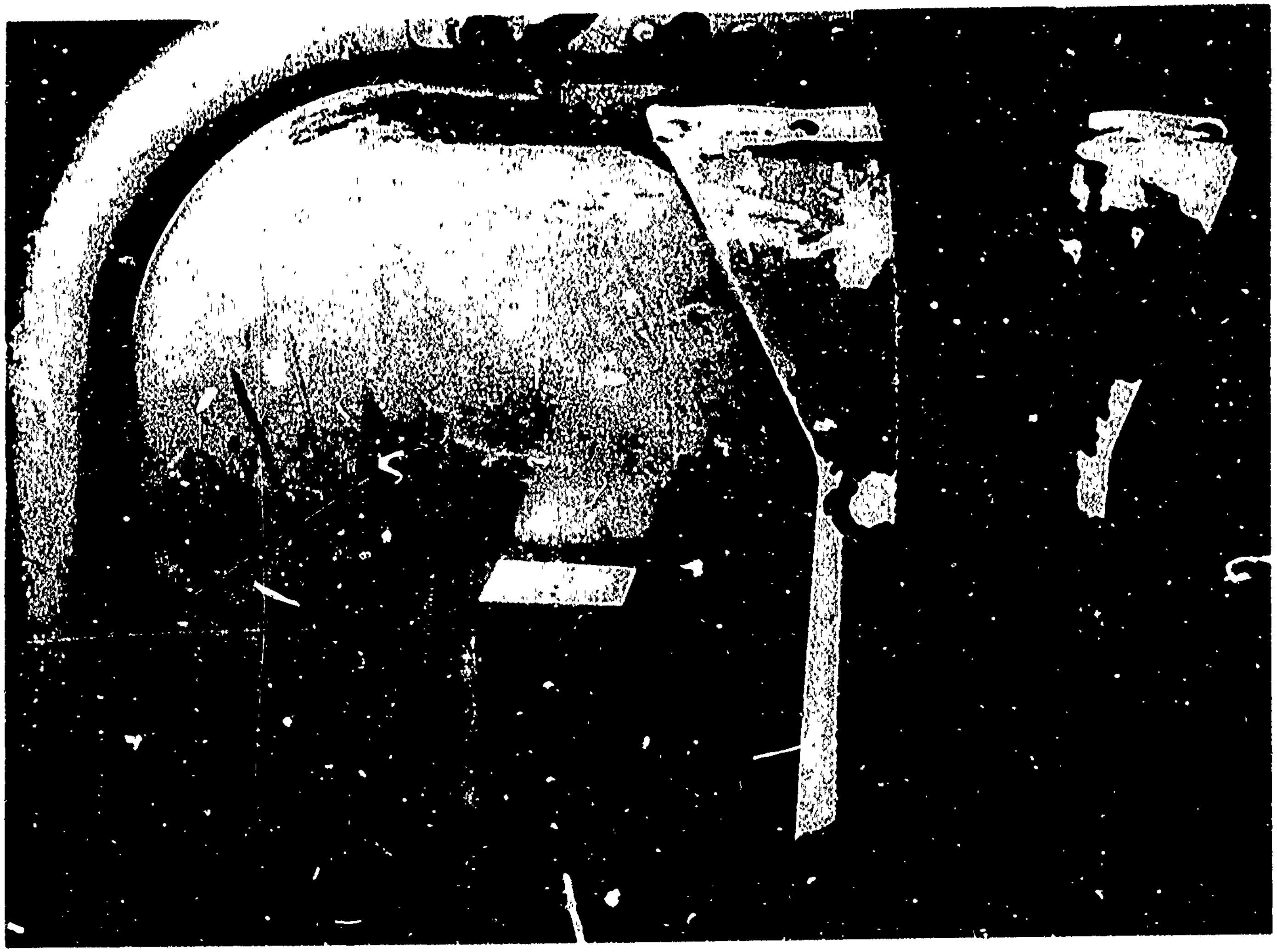

Figure 12. Position of Sonar Operator's Seat Accelerometer Package in the SH-3A

Figure 13. Position of Pilot's Seat Accelerometer Package in the SH-3A

Figure 14. Microphone Position in CH-47C

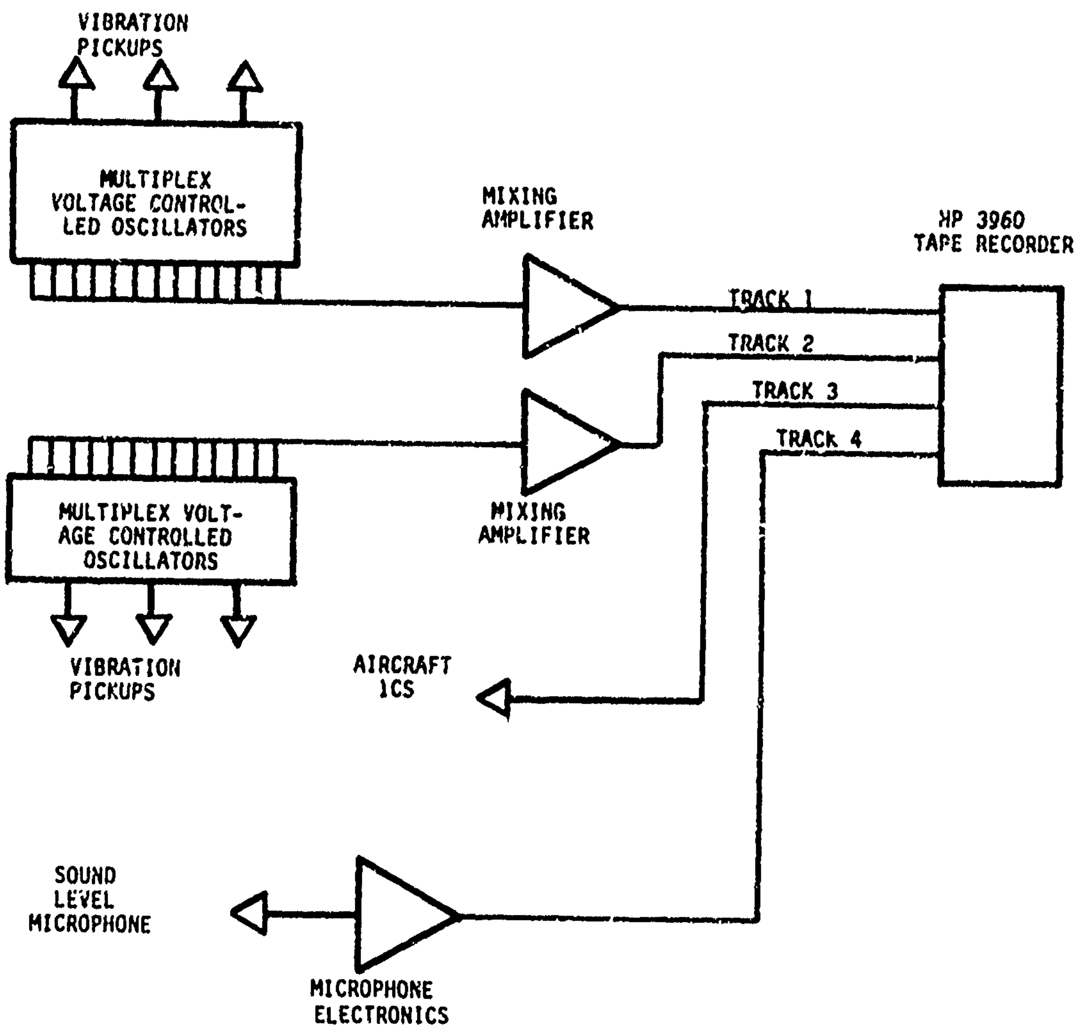

Figure 15. Simplified Schematic of Portable Data Package

Figure 15. Simplified Schematic of Portable Data Package

2.2 Mission Profiles

2.2.1 SH-3A Mission Profile

The mission chosen as representative of the primary function of the SH-3A was an ASW sonar search mission. An elapsed time/maneuver description of this mission is given in Table I. This mission was a simulated sonar search in that cold weather conditions prohibited flights over water, however, it is reasonable to assume that the basic vibration characteristics should be similar to an actual sonar search mission. The mission duration was two hours and data collection was continuous throughout this time period. This mission consists of the helicopter flying to a point where a submarine is suspected, at this point the helicopter descends to 40 ft. and hovers. During the hover the sonar transducer is lowered into the water. The helicopter remains in hover until a submarine is detected or until it is determined that no submarine is present in the immediate search area. This process is repeated at other search areas until the mission is completed. In this study five simulated sonar searches were attempted with the pilot adhering to the rigid altitude margin required of actual sonar dips. Table II gives the elapsed time/maneuver description of the SH-3A discrete component flight as recorded.

2.2.2 CH-47C Mission Profile

The mission chosen as representative of the primary function of the CH-47C was a combination helicopter recovery/troop resupply mission typical of Vietnam. An elapsed time/maneuver description of this mission is given in Table III. The helicopter recovery portion of this mission involved hoisting a 6000 lb UH-1A and carrying it to a designated drop point. At the drop point the UH-1A was lowered until the hoist cable was completely slack. This process was repeated four times. Figure 16 shows the CH-47C lifting the UH-1A. The troop resupply portion was merely a repetition of the above with no external load. This mission segment was repeated three times. The duration of the entire mission was two hours. During the recording of this mission profile the tape recorder made several inadvertent stops due to a loose connector. These stops resulted in momentary spikes on the otherwise continuous tape record. In as much as this tape was planned as a device for driving a human simulator, such spikes were unacceptable. To overcome this problem these spikes were erased and the resulting dead space replaced with the vibration recorded immediately prior to the occurance of the spike. The resulting tape record was free of any spurious spikes and representative of the mission profile desired. Table IV gives the elapsed time/maneuver description of the CH-47C discrete component flight as recorded.

Figure 16. CH-47C Hoisting UH-1A

TABLE I

SH-3A ASW Mission Flight

Mission Segment	Altitude (ft)	Air Speed (knots)	Elapsed Time (IRIG B)
Climb to Alt.	0-1500	70	0:00 - 3:00
Cruise	1500	100	3:00 - 14:30
Descend to Hover	1500-500	70	14:30 - 17:00
Sonar Dip Hover	500	0	17:00 - 27:00
Climb	500-1500	70	27:00 - 28:00
Cruise	1500	70	28:00 - 30:45
Descend to Hover	1500-500	70	30:45 - 31:45
Sonar Dip Hover	500	0	31:45 - 41:00
Climb	500-1500	70	41:00 - 42:20
Cruise	1500	70	42:20 - 46:20
Descend to Hover	1500-500	70	46:20 - 48:15
Sonar Dip Hover	500	0	48:15 - 58:15
Climb	500-1500	70	58:15 - 60:00
Cruise	1500	70	60:00 - 64:00
Descend to Hover	1500-500	70	64:00 - 66:50
Sonar Dip Hover	500	0	66:50 - 76:50
Climb	500-1500	70	76:50 - 78:40
Cruise	1500	70	78:40 - 83:00
Descend to Hover	1500-500	70	83:00 - 85:30
Sonar Dip Hover	500	0	85:45 - 95:45
Climb	500-1500	70	95:45 - 97:30
Return Cruise	1500	100	97:30 -118:30
Approach - Land	1500-0	70	118:30 -120:30

TABLE II

SH-3A Component Maneuver Flight

Component	Altitude (ft)	Air Speed (knots)	Elapsed Time (IRIG B)
Hover	22	0	0:00 - 5:43
Cruise	22	20	8:00 - 11:45
Cruise	500	70	13:05 - 17:50
Cruise	500	100	19:36 - 23:45
Cruise	500	120	25:10 - 29:34
Normal Climb*	500 ft/min	70	31:09 - 33:20
Normal Descent	500 ft/min	70	33:30 - 35:40
Rapid Climb	1500 ft/min	70	36:05 - 37:10
Rapid Descent	1500 ft/min	70	37:23 - 38:45
Stand. Rate Turn (left)	600	100	38:50 - 43:50
Stand. Rate Turn (right)	600	100	45:20 - 50:37
Double St.Rate Turn (left)	600	100	52:00 - 56:20
Double St.Rate Turn (right)	600	100	57:38 - 62:20
45° Turn (left)	600	70	63:46 - 68:17
45° Turn (right)	600	70	70:00 - 74:20

*Climb and descents limited due to low ceiling

TABLE III

CH-47C Helicopter Recovery Mission Flight

Mission Segment	Altitude (ft)	Air Speed (kts)	Elapsed Time (IRIG B)
Hoist UH-1A	20	0	0:00 - 3:55
Climb	600 ft/min	60	3:55 - 6:15
Cruise	1500	60	6:15 - 16:30
Descend	1000 ft/min	50	16:30 - 17:10
Release UH-1A	20	0	17:10 - 18:30
Climb	500 ft/min	60	18:30 - 19:43
Cruise	1500	60	20:00 - 29:44
Descend	1000 ft/min	50	29:44 - 31:50
Release UH-1A	20	0	31:50 - 32:10
Climb	500 ft/min	60	32:10 - 33:50
Cruise	1500	60	34:00 - 42:40
Descend	1000 ft/min	50	42:40 - 44:20
Release UH 1A	20	0	44:20 - 45:10
Climb	500 ft/min	60	45:20 - 46:50
Cruise	1500	65	46:50 - 54:13
Descend	1000 ft/min	50	54:13 - 56:10
Release UH-1A*	20	0	56:10 - 57:00
Hover	20	0	57:00 - 66:45
Climb	1000 ft/min	80	66:45 - 68:30
Cruise	1500	100	68:30 - 78:00
Descend	1000 ft/min	80	78:00 - 80:00
Climb	1000 ft/min	80	80:00 - 81:40
Cruise	1500	100	81:40 - 92:30
Descend	1000 ft/min	80	92:30 - 94:20
Climb	1000 ft/min	80	94:20 - 96:30
Cruise	1500	100	96:30 - 104:20
Descend	1000 ft/min	80	104:20 - 105:40
Climb	1000	80	105:40 - 107:20
Return	1500	100	107:20 - 112:10

*Final Release of UH-1A

TABLE IV

CH-47C Component Maneuver Flight

Component	Altitude(ft)	Air Speed (knots)	Elapsed Time (IRIG B)
Hover	20	0	0:00 - 6:00
Rapid Climb	2000 ft/min	80	6:45 - 10:05
Rapid Descent	2000 ft/min	80	10:25 - 13:30
Normal Climb	1000 ft/min	80	14:00 - 20:00
Normal Descent	1000 ft/min	80	20:15 - 24:50
Cruise	1500	40	26:30 - 34:20
Cruise	1500	100	35:30 - 43:30
Cruise	1500	130	46:45 - 56:45
Cruise	1500	145	59:00 - 69:00
Hover	1500	0	71:00 - 78:00
St. Rate Turn (left)	1500	100	79:20 - 84:30
St. Rate Turn (right)	1500	100	84:40 - 89:45
Double St. Rate Turn (left)	1500	100	92:45 - 97:45
Double St. Rate Turn (right)	1500	100	100:00 - 105:00
30° Turn (left)	1500	70	106:15 - 108:40
30° Turn (right)	1500	70	108:55 - 111:40

2.3 Data Collection Procedures

Vibration, cabin noise, and ICS commentary were originally recorded on 1/4-inch magnetic tape. The multiple vibration pick-up points were recorded in an FM multiplex format and subsequently de-multiplexed and re-recorded, together with cabin noise and ICS commentary, on one-inch, 14-channel magnetic tape. In those cases where more than 14 channels of information were originally recorded, the additional data were simultaneously re-recorded on 1/2-inch, 7 channel magnetic tape. The tape format for the four data flights is shown in Table V.

ach accelerometer was calibrated immediately before each data flight and the +1, 0, - 1g reading was recorded on the front of the 1/4-inch magnetic tape. Table VI shows the status of the data collected for each accelerometer for the four flights. In order to avoid recording local resonances and distorting the overall vibration picture associated with the structure of interest, the triaxial accelerometer packages were aligned directly with this structure whenever possible. In the two cases where this was not possible (the rudder pedal and collective control stick) a minimum of bracketry was utilized. In following this recommended procedure it should be emphasized that the vibration levels recorded at each point are in reference to a coordinate system collinear with the structure measured and not the physiological reference system of the pilot. For convenience of reference, Table VII provides the angular displacement from the pilot's physiological coordinate system of all the accelerometer packages.

Sound pressure level measurements were recorded directly with a B and K sound pressure level meter in order to provide an amplitude reference for the recorded noise measurements. These levels are shown in Tables VIII and IX for the CH-47C and the SH-3A respectively.

2.4 Data Analysis

A General Radio model 1925 third octave-band multifilter was used to perform a spectrum analysis of the vibration tapes. The third octave-band analysis was over the frequency range of interest (1-30 Hz) and included all vibration pickup points on both helicopters across four representative maneuvers. For each maneuver/helicopter/accelerometer combination two independent one-minute time records were analyzed and their resulting amplitude by frequency plots superimposed on the same spectrogram. This procedure was followed in order to check the assumption of stationarity, i.e. to determine the generalizability of a given record. The spectrograms resulting from the third octave-band analysis are presented in appendixes A and B for SH-3A and CH-47C respectively. It should be noted that the vibration levels for the rudder pedal and collective control stick shown in Appendixes A and B represent those levels recorded with the pilot in contact with the controls while in control of the aircraft. The vibration recorded at the collective control

TABLE V

Magnetic Tape Format

Channel	CH-47C Mission	Ch-47C Component	SH-3A Mission	SH-3A Component
One Inch 14 Channel Tapes				
1	Rudder X	Thrust Lever X	Inst. Panel X	Rudder X
2	Rudder Y	Thrust Lever Y	Inst. Panel Y	Rudder Y
3	Rudder Z	Thrust Lever Z	Inst. Panel Z	Rudder Z
4	Thrust Lever X	Inst. Panel X	Front Seat X	Collective X
5	Thrust Lever Y	Inst. Panel Y	Front Seat Y	Collective Y
6	Thrust Lever Z	Inst. Panel Z	Front Seat Z	Collective Z
7	Inst. Panel X	Front Seat X	Sonar Op.Seat X	Inst. Panel X
8	Inst. Panel Y	Front Seat Y	Sonar Op.Seat Y	Inst. Panel Y
9	Inst. Panel Z	Front Seat Z	Sonar Op.Seat Z	Inst. Panel Z
10	Front Seat X	Bite Bar	*	Front Seat X
11	Front Seat Y	*	*	Front Seat Y
12	Front Seat Z	Cabin Noise	Cabin Noise	Front Seat Z
13	ICS	ICS	ICS	Bite Bar
14	IRIG Time Code	IRIG Time Code	IRIG Time Code	IRIG Time Code
One Half Inch 7 Channel Auxiliary Tapes				
1	Bite Bar	*	*	Rear Seat X
2	Inst Panel (left) X	*	*	Rear Seat Y
3	Inst Panel (left) .	*	*	*
4	Cabin Noise	*	*	Cabin Noise
5	ICS	*	*	*
6	IRIG Time Code	*	*	*
7	*	*	*	IRIG Time Code

*No information on This Channel

TABLE VI

Data Status Matrix

Accelerometer	SH-3A Component	SH-3A Mission	CH-47C Component	CH-47C Mission
Bite Bar Z	C	M	C	C
Rudder X	C	M	M	C
Y	C	M	M	C
Z	C	M	M	C
Collective X	C	M	C	C
Y	C	M	M	C
Z	C	M	C	C
Inst. Panel (R) X	C	C	C	C
Y	C	C	C	C
Z	C	C	C	C
Frt.Seat X	C	C	C	C
Y	C	C	C	C
Z	C	C	C	C
Rear Seat X	C	C	NA	NA
Y	C	C	NA	NA
Z	M	C	NA	NA
Inst. Panel (L) X	NA	NA	NA	C
Y	NA	NA	NA	C
Z	NA	NA	NA	M

C implies complete data throughout flight
M implies data missing throughout flight
NA implies no attempt made on specific flight

TABLE VII

Angular Displacement of Accelerometer Packages from Pilot's Physiological Reference System

		Angular Displacement (Degrees)		
	Accelerometer Package	Pitch	Roll	Yaw
	Rudder Pedal	12.5 Down	3.5 Right	Collinear*
CH-47C	Instrument Panel	16.0 Down	Collinear	Collinear
	Thrust Lever	4.0 Down	Collinear	Collinear
	Front Seat	10.0 Up	3.5 Left	18.0 Left
	Rudder Pedal	11.0 Down	Collinear	Collinear
	Instrument Panel	20.0 Down	Collinear	Collinear
SH-3A	Collective	Collinear	Collinear	Collinear
	Front Seat	14.0 Down	14.0 Left	Collinear
	Sonar Op Seat	14.0 Down	14.0 Left	Collinear

*Collinear with pilot's physiological reference system

TABLE VIII

Sound Pressure Level (db re .0002 microbar) for the CH-47C Under Loaded and Unloaded Conditions

Center Frequency (Hz)	Hauling UH-1A*	Empty**
31.5	117	120
63	105	110
125	100	104
250	97	102
500	92	94
1000	96	97
2000	102	101
4000	93	94
8000	81	81
16000	66	67
31500	42	42
Overall	119	122

*Hauling UH-1A on sling at 65 knots straight and level flight

** No load on sling at 100 knots straight and level flight

TABLE IX

Sound Pressure Levels (db re .0002 microbar) for the SH-3A under Three Flight Conditions

Center Frequency(Hz)	Cruise (100 kts)	Cruise (70 kts)	Hover
31.5	100	96	92
63	101	98	97
125	97	97	97
250	97	94	97
500	95	91	94
1000	90	90	90
2000	85	84	86
4000	80	80	80
8000	84	86	78
16000	86	86	84
31500	59	58	59
Overall	110	109	102

stick and rudder pedal free of pilot contact is shown in appendix C for the SH-3A.

Before analysis of a given channel, a sine wave calibration equivalent to the d.c. level obtained in the preflight calibration for that accelerometer was generated. By this procedure all channels of data were standardized such that the voltage associated with 1.0g acceleration represented a 50 db reading on the multifilter, i.e., all resulting spectrograms are directly comparable.

3.0 Results and Discussion

At the completion of the thrid octave-band analysis a General Radio model 1925-9000 tenth octave-band multifilter was used to pinpoint more closely the exact frequencies associated with peak acceleration. Three predominant frequencies were found for both helicopters: 3.9 Hz (1/rev), 12.0 Hz (3/rev), and 24.0 Hz (n/rev) for the CH-47C and 3.4 Hz (1/rev), 6.8 Hz (2/rev), and 17.0 Hz (n/rev) for the SH-3A. Tables X and XI represent the rms-g levels found at these three frequencies for the CH-47C and SH-3A respectively. Table XII represents a comparison of the rms-g levels associated with the three peak frequencies recorded in the SH-3A at the rudder pedal and collective control stick with pilot in normal contact with that control versus those levels found when the particular control was free.

The results of the spectrum analysis of the vibration tapes indicate that in the area of concern (1-30 Hz), vibration in both helicopters is a complex wave form exhibiting predominant power at three discrete frequencies. These frequencies correspond to the main rotor head rate (1/rev), a harmonic of this frequency (2/rev for the SH-3A and 3/rev for the CH-47C) and the blade rate (n/rev). This pattern is evident across all axes although most predominant in the vertical (Z) axis.

From a physiological standpoint the peak at the 1/rev rate is of particular importance since this rate falls at the lower end of the frequency range comprising whole body resonance (3-7 Hz). In this range the body acts as an amplifier of vibration amplitude as it travels from the source through the body to the head. This phenomenon is plainly seen in Table X and XI when the rms-g levels for pilot's seat (Z-axis) are compared against the bite bar (pilot's head in the Z axis). At the 1/rev frequency the vibration amplitude is considerably greater at the pilot's head than at the seat,at the middle frequency the amplitude is almost unaffected as it is transmitted from the pilot's seat to his head; while at the n/rev frequency the amplitude at the pilot's head is only a fraction of the seat amplitude. These results imply that while the vibration recorded at the various pickup points at the 1/rev frequency is usually considerably less than at the n/rev frequency, the impact on pilot performance (where the pilot is in direct contact with the vibrating structure) is most likely greatest from the 1/rev component. It is therefore at this rate that major emphasis in vibration attenuation should be placed to have an optimum impact on pilot performance.

TABLE X

RMS-G levels associated with the Predominant Frequencies for the CH-47C
Across Four Selected Maneuvers

	MANEUVER											
	Hover			40 Kt Cruise			100 Kt Cruise			Double Std Rate Turn		
Accelerometer	3.9 Hz	12.0 Hz	24.0 Hz	3.9 Hz	12.0 Hz	24.0 Hz	3.9 Hz	12.0 Hz	24.0 Hz	3.9 Hz	12.0 Hz	24.0 Hz
Rudder X	.026	.050	.016	---*	---	---	.022	.045	.016	---	---	---
Rudder Y	.040	.040	.056	---	---	---	.034	.045	.063	---	---	---
Rudder Z	.030	.060	.080	---	---	---	.022	.050	.080	---	---	---
Thrust LeverX	.034	.070	.080	.040	.063	.090	.031	.056	.100	.031	.056	.100
Thrust LeverY	---	---	---	---	---	---	---	---	---	---	---	---
Thrust LeverZ	.050	.056	.115	.045	.100	.030	.045	.115	.070	.045	.100	.034
Inst.Panel X	.022	.022	.090	.022	.026	.080	.026	.016	.070	.022	.026	.70
Inst.Panel Y	.045	.040	.070	.045	.063	.063	.040	.056	.063	.045	.056	.031
Inst.Panel Z	.016	.063	.320	.016	.040	.285	.031	.050	.250	.022	.045	.306
Pilot Seat X	.022	.090	.135	.131	.056	.100	.040	.070	.125	.045	.062	.115
Pilot Seat Y	.040	.045	.125	.034	.070	.070	.026	.063	.090	.025	.056	.070
Pilot Seat Z	.020	.045	.100	.016	.030	.070	.016	.016	.050	.014	.016	.060
Bite Bar	.030	.022	.016	.056	.020	.016	.056	.016	.014	.062	.014	.010

*Data Missing

TABLE XI

RMS-G Levels Associated with the Predominant Frequencies for the SH-3A
Across Four Selected Maneuvers

	MANEUVER											
	Hover			20 Kt Cruise			100 Kt Cruise			Double Std Rate Turn		
Accelerometer	3.4 Hz	6.8 Hz	17.0 Hz	3.4 Hz	6.8 Hz	17.0 Hz	3.4 Hz	6.8 Hz	17.0 Hz	3.4 Hz	6.8 Hz	17.0 Hz
Rudder X	.022	.012	.031	.018	.010	.034	.016	.014	.090	.026	.018	.056
Rudder Y	.016	.015	.045	.016	.026	.050	.016	.034	.063	.026	.034	.063
Rudder Z	.016	.009	.034	.016	.006	.045	.014	.010	.050	.018	.006	.050
Collective X	.020	.011	.031	.018	.008	.045	.016	.012	.063	.014	.012	.053
Collective Y	.018	.014	.100	.020	.022	.090	.016	.031	.225	.022	.022	.225
Collective Z	.026	.016	.040	.020	.014	.056	.020	.020	.056	.031	.016	.056
Inst.Panel X	.026	.016	.031	.020	.018	.034	.020	.026	.020	.026	.026	.023
Inst.Panel Y	.031	.031	.014	.022	.056	.056	.020	.080	.031	.026	.070	.034
Inst.Panel Z	.022	.034	.045	.018	.016	.063	.018	.045	.050	.022	.040	.050
Pilot Seat X	.031	.012	.034	.020	.010	.125	.018	.011	.063	.020	.008	.100
Pilot Seat Y	.026	.014	.063	.020	.012	.150	.018	.020	.100	.020	.016	.115
Pilot Seat Z	.026	.012	.040	.020	.009	.100	.020	.012	.040	.026	.011	.045
Bite Bar	.034	.011	.008	.022	.008	.020	.022	.011	.011	.018	.011	.010

The large rms-g levels recorded in the Z-axis of the instrument panel for the CH-47C at the n/rev frequency suggest a potential problem area: As previously mentioned the body attenuated the majority of vibration amplitude at the n/rev frequency, thus there is a motion phase lag between the pilot's head and the instrument panel. It would seem that for the instrument panel (and any other structure for which the pilot has no direct contact but from which he must extract information) the n/rev frequency is of critical concern. For such structures vibration attenuation and absorption emphasis should be placed at the n/rev frequency. This situation is of particular importance in light of the previously mentioned differential effect of performance between a vibrating target with the man static and a vibrating man viewing a static target. It is not clear what effect this out-of-phase condition has on human performance, but it may create special problems of its own which need further investigation.

A closer examination of Table XII reveals that the effects on vibration amplitude of pilot contact with a control are dependent on frequency. At 3.4 Hz (1/rev) contact with the control resulted in a slight attenuation in the recorded rms-g level at that control, at 6.8 Hz there is actually an intensification in vibration amplitude, while at 17 Hz a rather large attenuation is apparent. These results are in line with the fact that 6.8 Hz is within the range of the resonance frequency of both the arm and the leg. It is therefore apparent that with respect to rudder pedal and control stick vibration, major emphasis should be placed at this intermediate frequency.

4.0 Application of the Data

The final point of concern is the representativeness of the obtained vibration data. It is obvious that a multitude of factors contribute to the exact vibration wave form found at any given time within a given helicopter. From a practical standpoint however the purely random components of helicopter vibration represent a rather insignificant portion of the total composite. This is evidenced by the correspondence between the two independent one-minute time records. These two records exhibited corresponding amplitude-frequency patterns for both helicopters across all maneuvers investigated. This fact coupled with the predictability of the three peak frequencies found, indicate that these data are generalizable to the vibration spectra found in SH-3A and CH-47C helicopters and should be useful in simulating these environments.

While it is theoretically possible to utilize all the recorded vibration data to individually drive each structure in a simulator, such an approach would be prohibitively expensive and would not be the most efficient approach in terms of information gained relevant

TABLE XII

COMPARISON OF RMS-G LEVELS RECORDED AT THE RUDDER PEDAL AND COLLECTIVE OF THE SH-3A WITH PILOT ON vs OFF THESE CONTROLS

Accelerometer	Contact with Controls	MANEUVER											
		Hover			20 KT CRUISE			100 KT CRUISE			Double Standard Rate Turn		
		3.4 Hz	6.8 Hz	17.0 Hz	3.4 Hz	6.8 Hz	17.0 Hz	3.4 Hz	6.8 Hz	17.0 Hz	3.4 Hz	6.8 Hz	17.0 Hz
Rudder X	ON	.022	.012	.031	.018	.010	.034	.016	.014	.070	.026	.018	.056
	OFF	.028	.011	.035	.020	.010	.160	.022	.013	.080	.025	.011	.069
Rudder Y	ON	.016	.015	.045	.016	.026	.050	.016	.034	.063	.026	.034	.063
	OFF	.017	.014	.040	.020	.017	.069	.017	.031	.069	.022	.028	.080
Rudder Z	ON	.016	.009	.034	.016	.006	.045	.014	.010	.050	.018	.006	.050
	OFF	.020	.009	.035	.014	.007	.056	.016	.009	.056	.017	.009	.063
Col. X	ON	.020	.011	.030	.018	.008	.045	.016	.012	.063	.014	.012	.056
	OFF	.022	.011	.043	.020	.010	.063	.017	.010	.056	.022	.008	.063
Col. Y	ON	.018	.014	.100	.020	.022	.090	.016	.031	.225	.022	.022	.225
	OFF	.022	.014	.173	.022	.014	.346	.020	.028	.276	.022	.025	.312
Col. Z	ON	.026	.016	.040	.020	.014	.056	.020	.020	.056	.031	.016	.056
	OFF	.028	.014	.069	.020	.011	.080	.025	.016	.100	.031	.014	.112

to human performance. Based on the fact that the human operator has primary contact with the seat, this interface should be driven directly with the vibration recordings on the magnetic tape. The obvious importance of the instrument panel as a source of information suggests that this structure be independently driven. Of major concern is the simulation of the seat and instrument panel such as to produce the unique out-of-phase condition found in the helicopter environment. It is rather doubtful that this situation could be adequately attained by whole cockpit vibration. The data relevant to the pilot's head, rudder pedal and collective control stick could be used indirectly to verify the simulator's response. Various damping and spring loaded devices could be utilized to accomplish a realistic vibration pattern for these controls without direct utilization of the data tapes.

Utilization of the cabin noise data would be somewhat dependent on the sound characteristics of the simulator. The investigator's major decision is whether to present the noise to the subjects via external speakers or earphones. While external speakers provide for a higher fidelity of simulation, this method is usually considerably more expensive. Research results relevant to this question are in conflict. Bromberger and Orrick (1972), using a simulated MAD task, found no difference in performance attributable to method of presentation; Sommer and Harris (1970), using a whole-body balancing task found poorer performance with speakers than earphones. It appears that the decision to use external speakers or earphones depends on the task involved as well as the physical characteristics of the simulation facility. Bromberger and Orrick (1972) also found no difference in performance between white noise and helicopter (HH-2D) noise matched for overall amplitude. This suggests that precise spectral matching across maneuvers is unnecessary. The extent to which it is necessary to achieve a correspondence between maneuver and overall noise amplitude is not clear; however, the above evidence suggests that precise correspondence would probably not be warranted.

5.0 Summary

As anticipated the peak frequencies found for both helicopters were the result of rotor head rate and harmonics of this frequency (especially the n/rev frequency). Each of the three peak frequencies was found to have particular relevance to human performance. The 1/rev frequency, being in the whole-body resonance range, was particularly significant due to the energy at this frequency being transmitted to the pilot's head. The 2/rev frequency (for the SH-3A) was the critical frequency at the rudder pedal and collective control stick since it is in the range of resonance for both the arm and leg. The n/rev frequency was the critical frequency at the instrument panel due to both the motion phase lag between the pilot's head and the displays and the low frequency response of the eye to a vibrating target.

The correspondence in both frequency and amplitude of vibration found between the two independent time samples for both helicopters across all maneuvers, together with the high degree of predictability of peak frequencies (1/rev and harmonics thereof) supported the contention that the random component of this vibration was relatively insigificant and thus gave support for the utilization of these tapes to simulate the vibration environment of these helicopters. It was suggested that the most valuable human performance data would be attained if the pilot's seat and instrument panel tapes were used to directly vibrate these structures in a simulator, while the remaining data would provide validation of simulation fidelity for the total simulation package.

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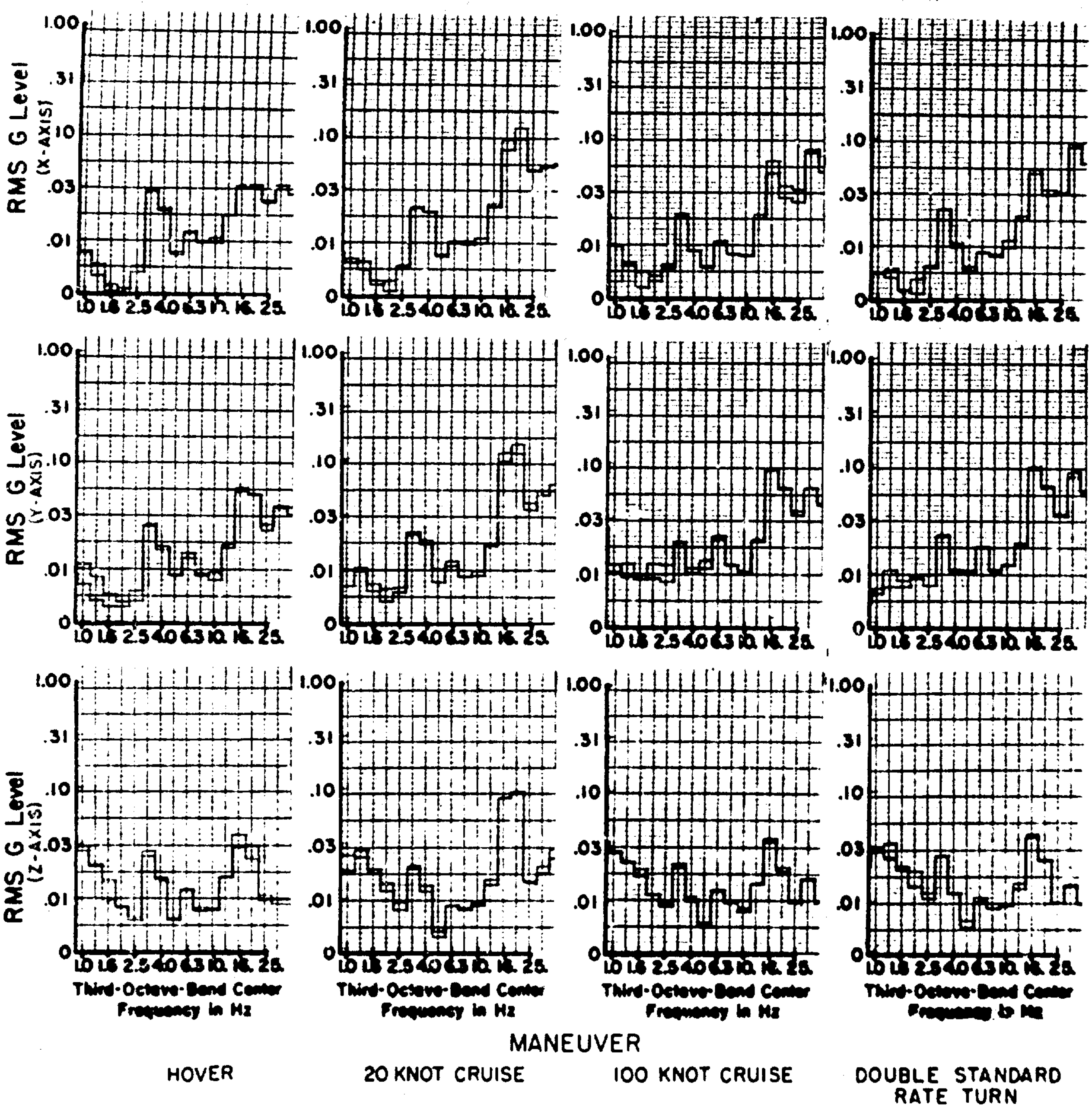
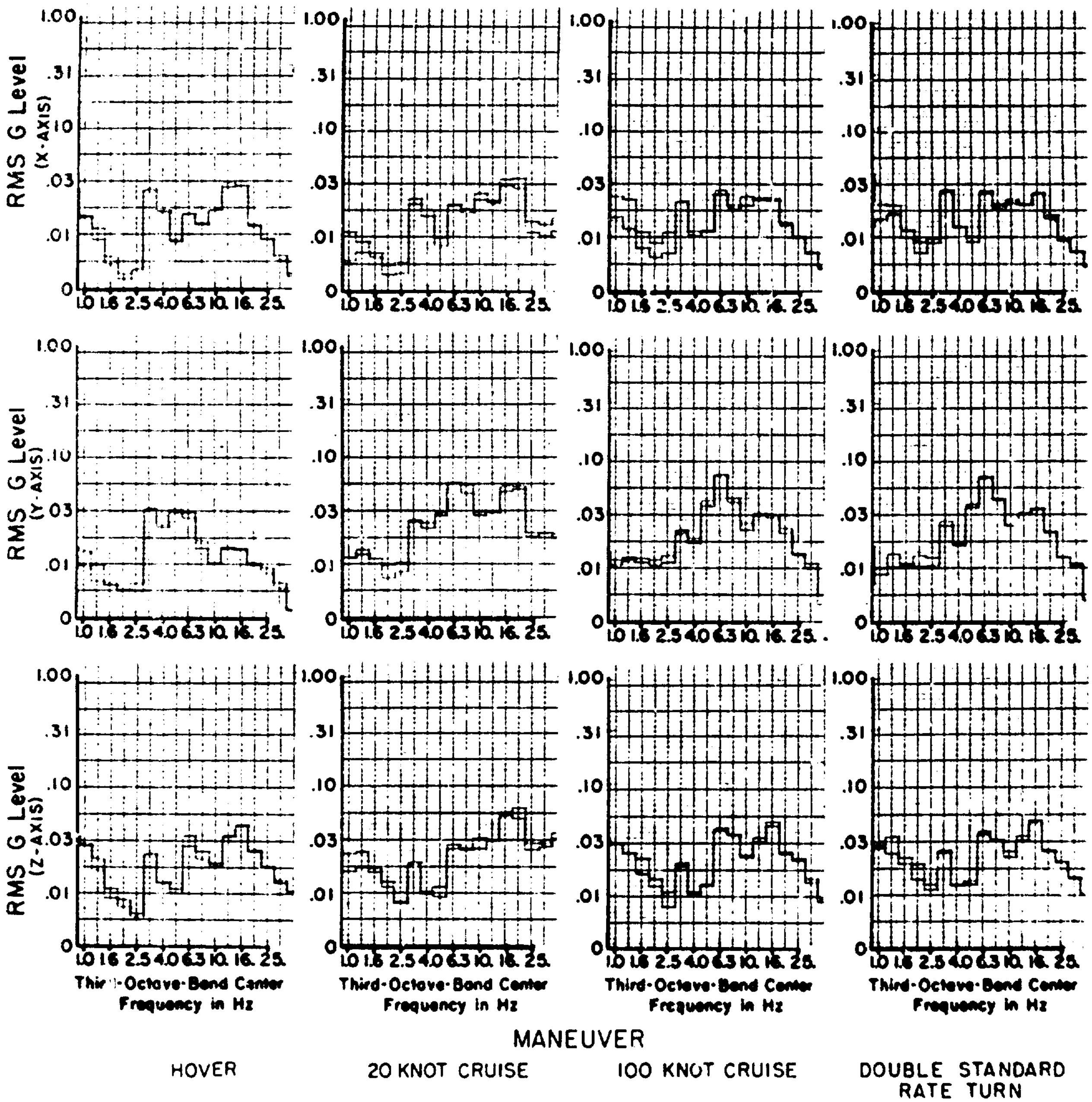
APPENDIX A

Third Octave-Band Spectrograms for the SH-3A Helicopter



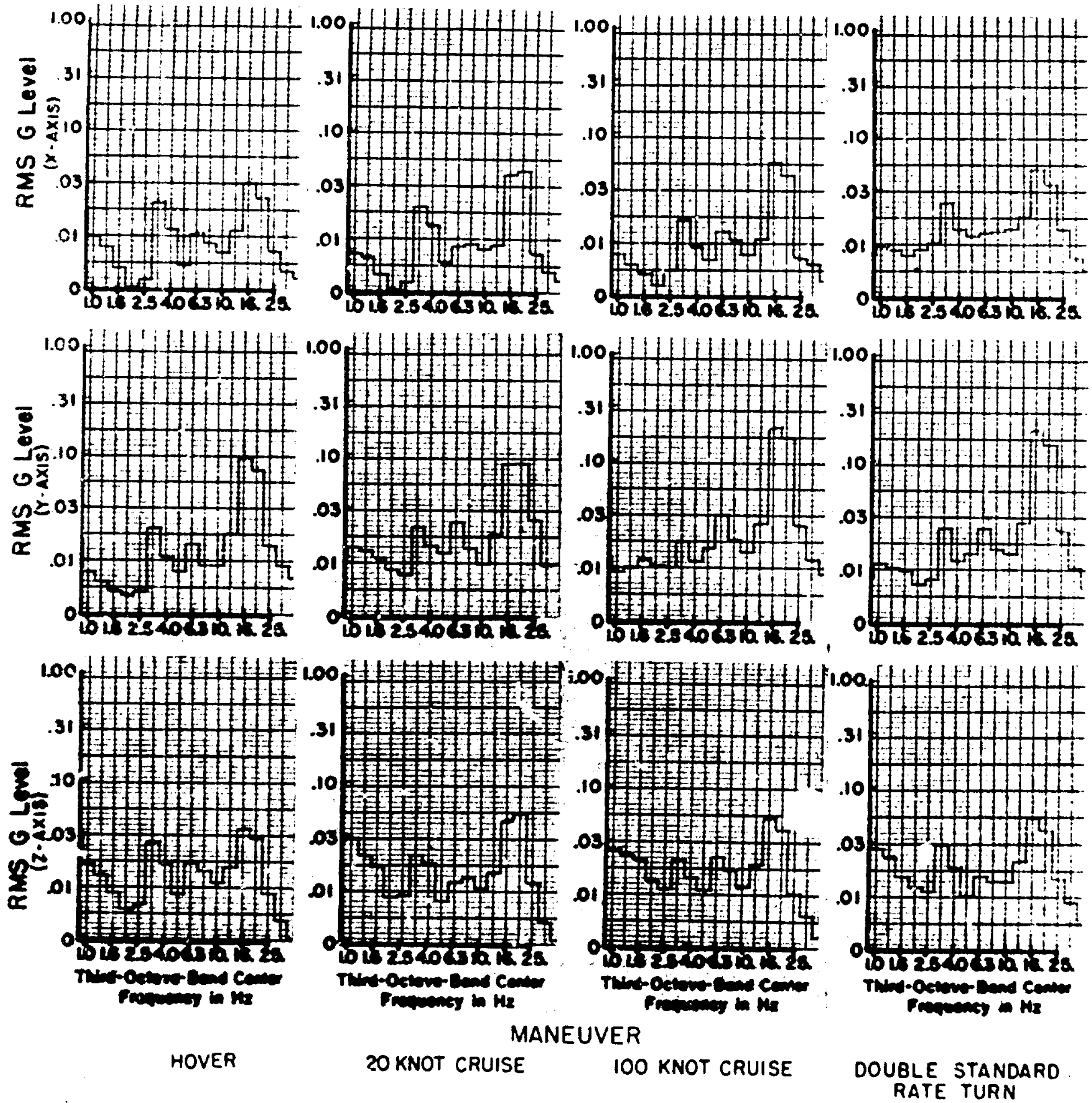
Pilot's Seat SH-3A

45

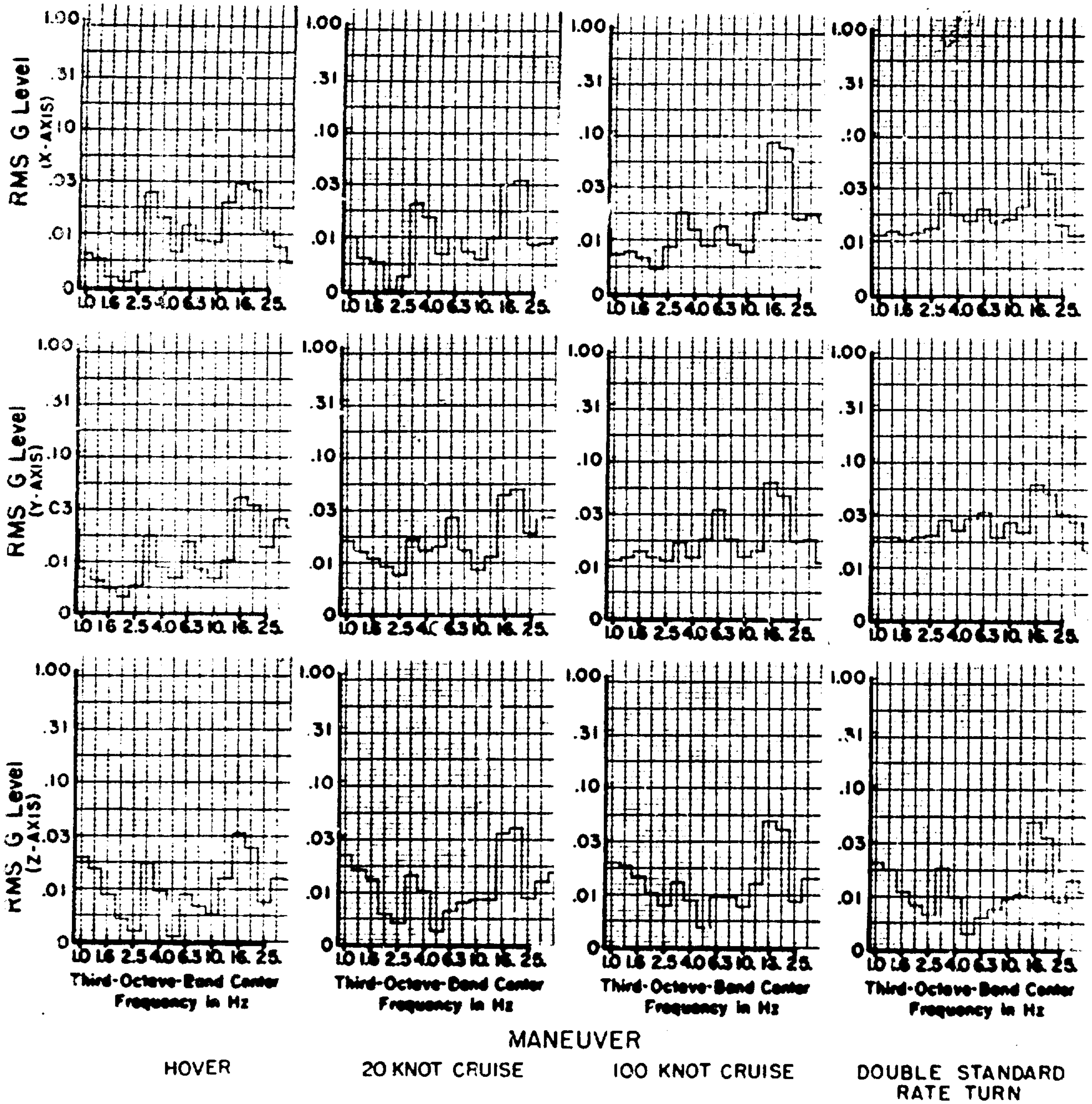


Instrument Panel SH-3A

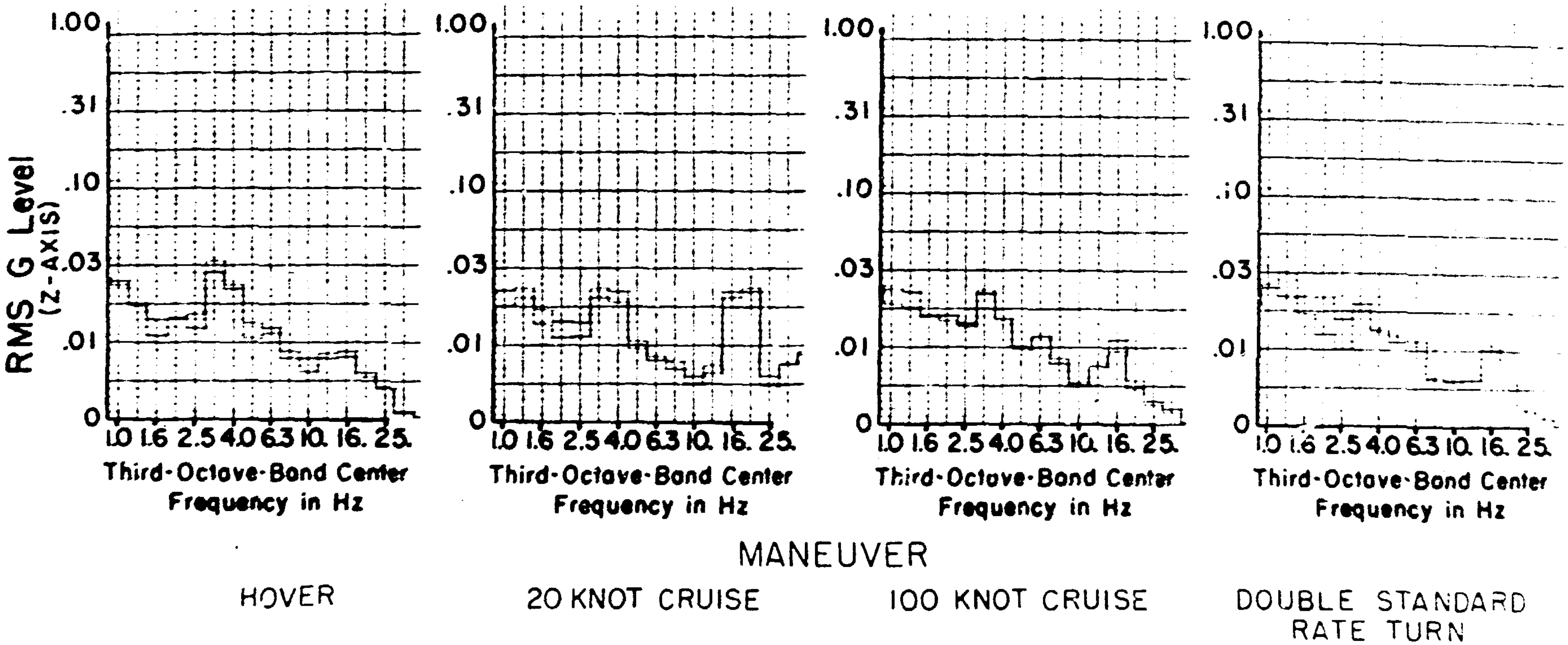
46



Collective Control Stick SH-3A



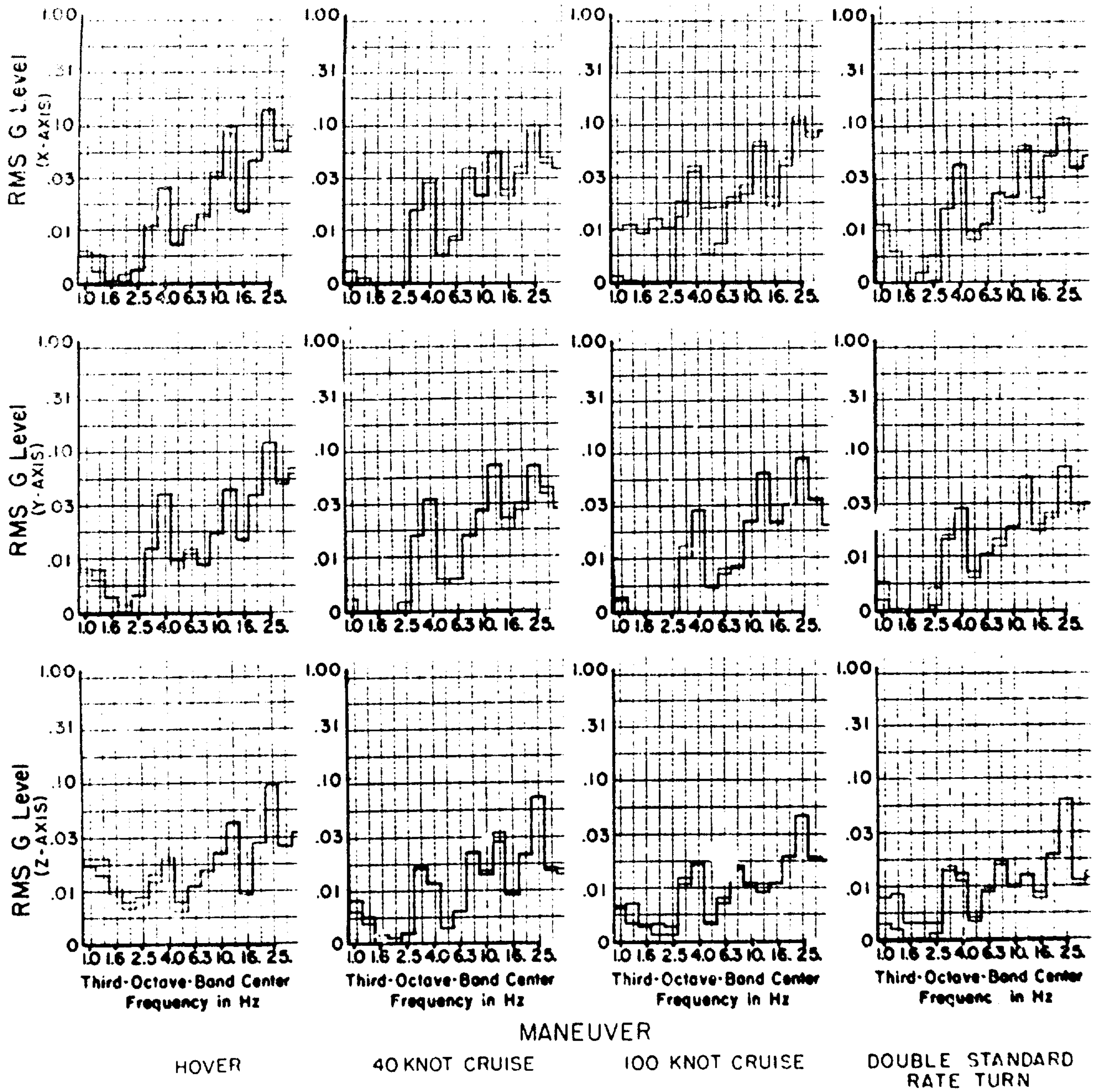
Rudder Pedal SH-3A



Pilot's Head SH-3A

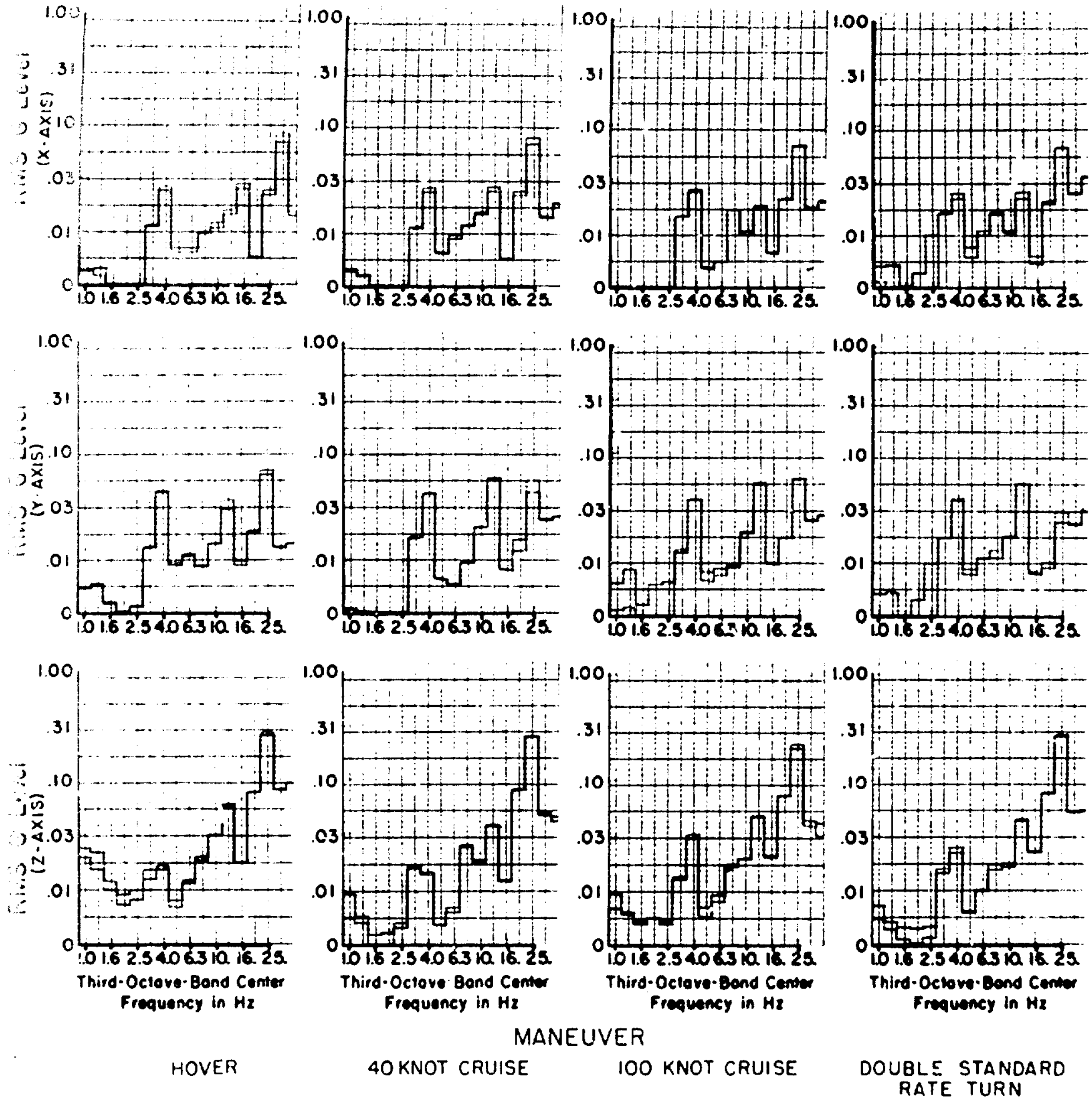
APPENDIX B

Third Octave-Band Spectrograms for the CH-47C Helicopter

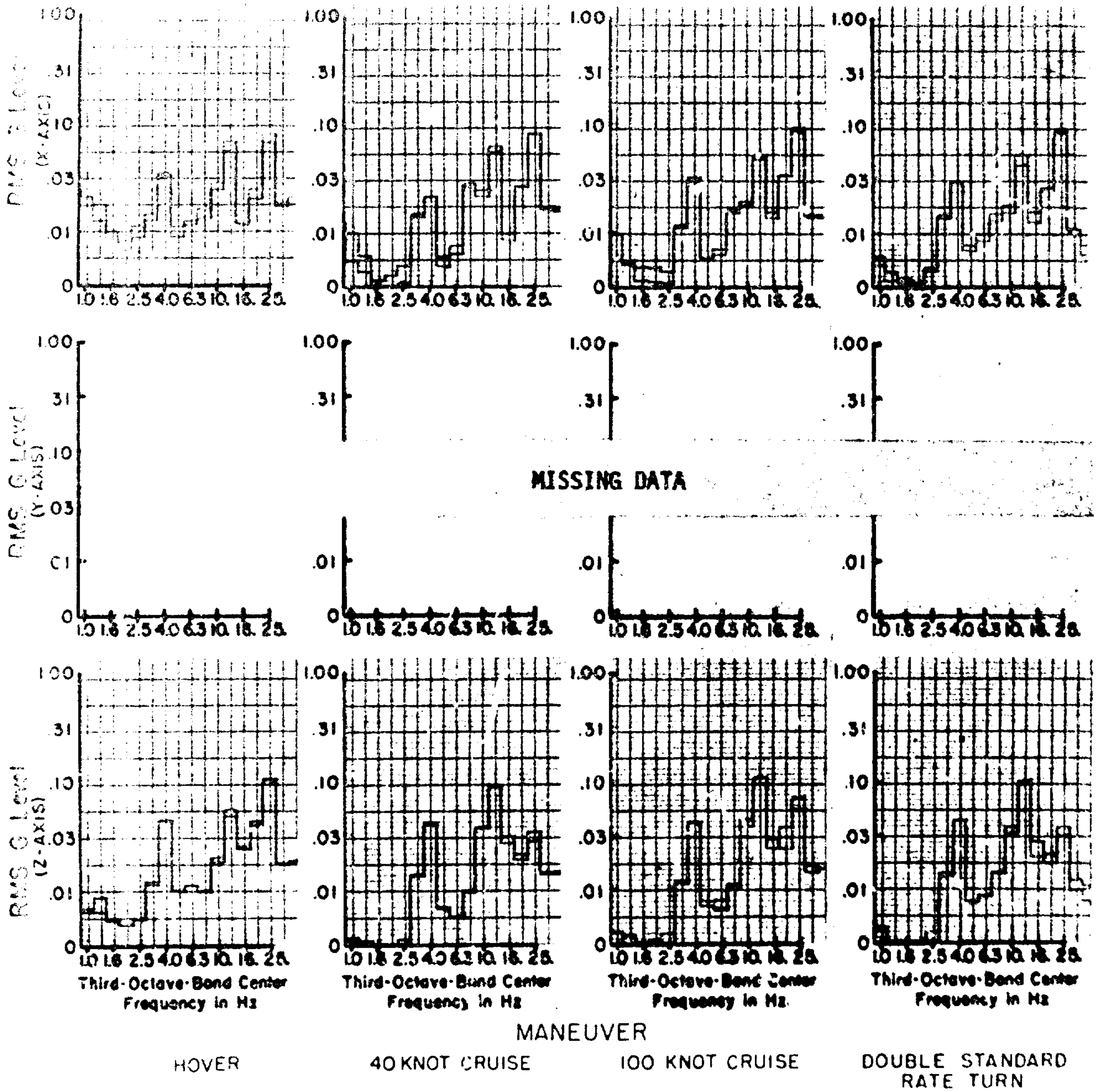


Pilot's Seat CH-47C

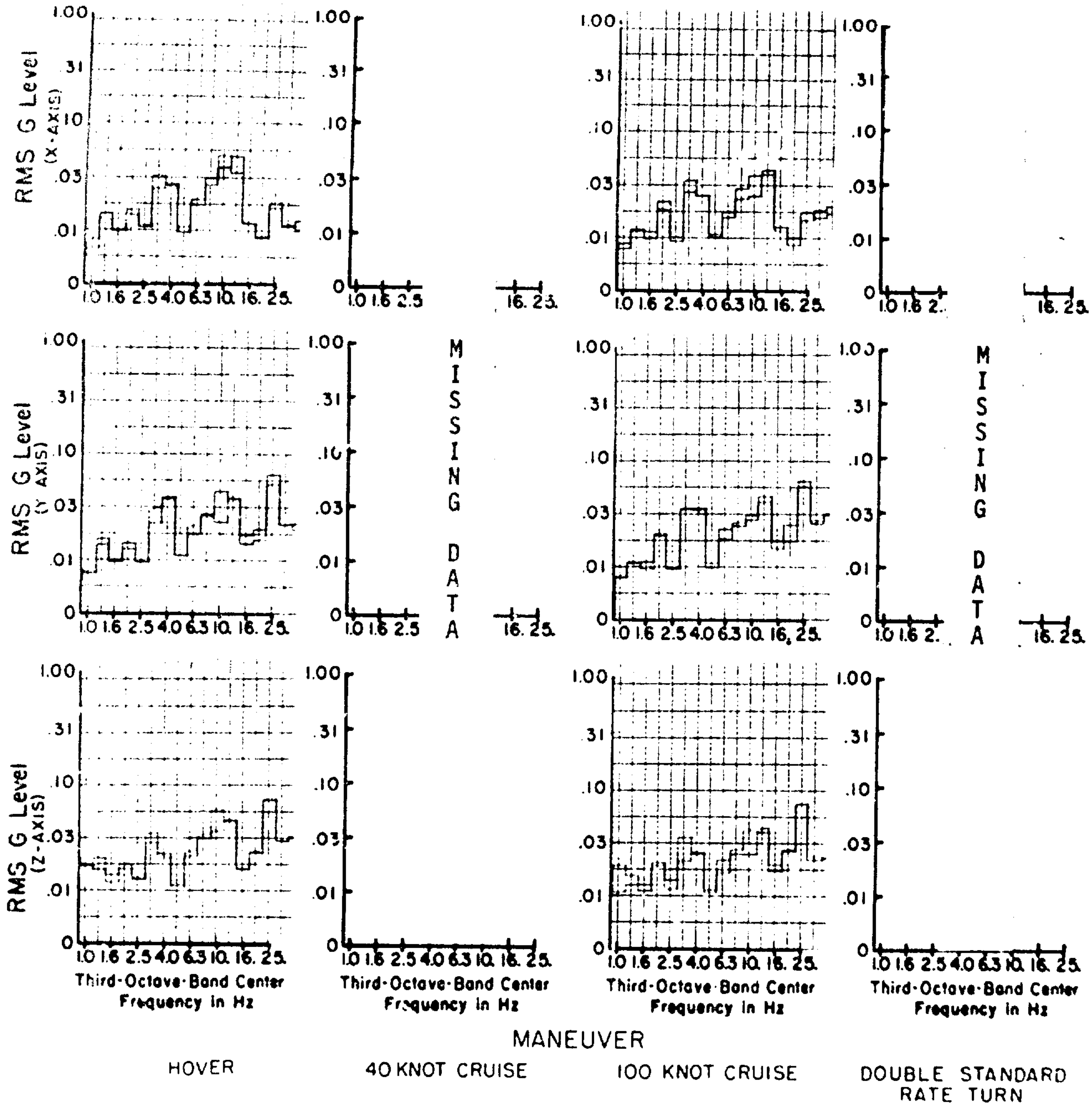
57



Instrument Panel CH-47C

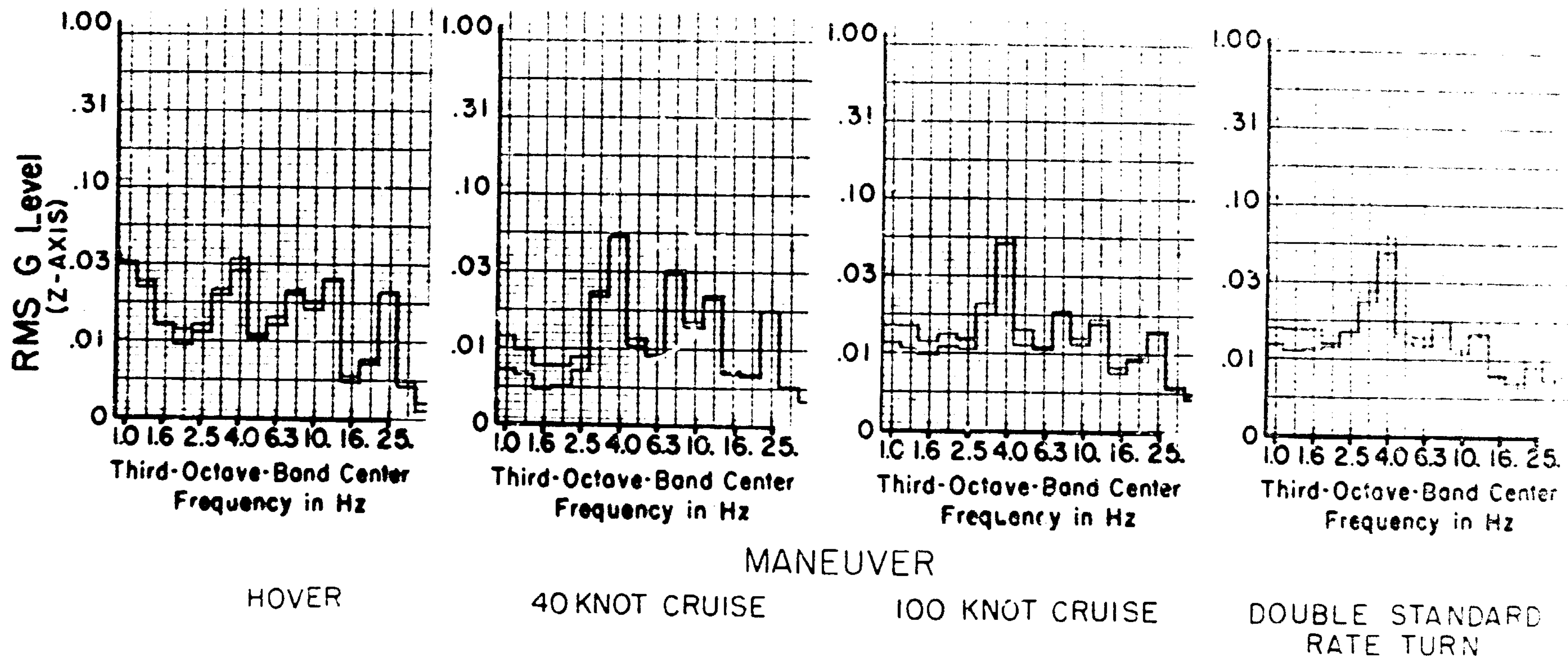


Thrust Lever CH-47C



Rudder Pedal CH-47C

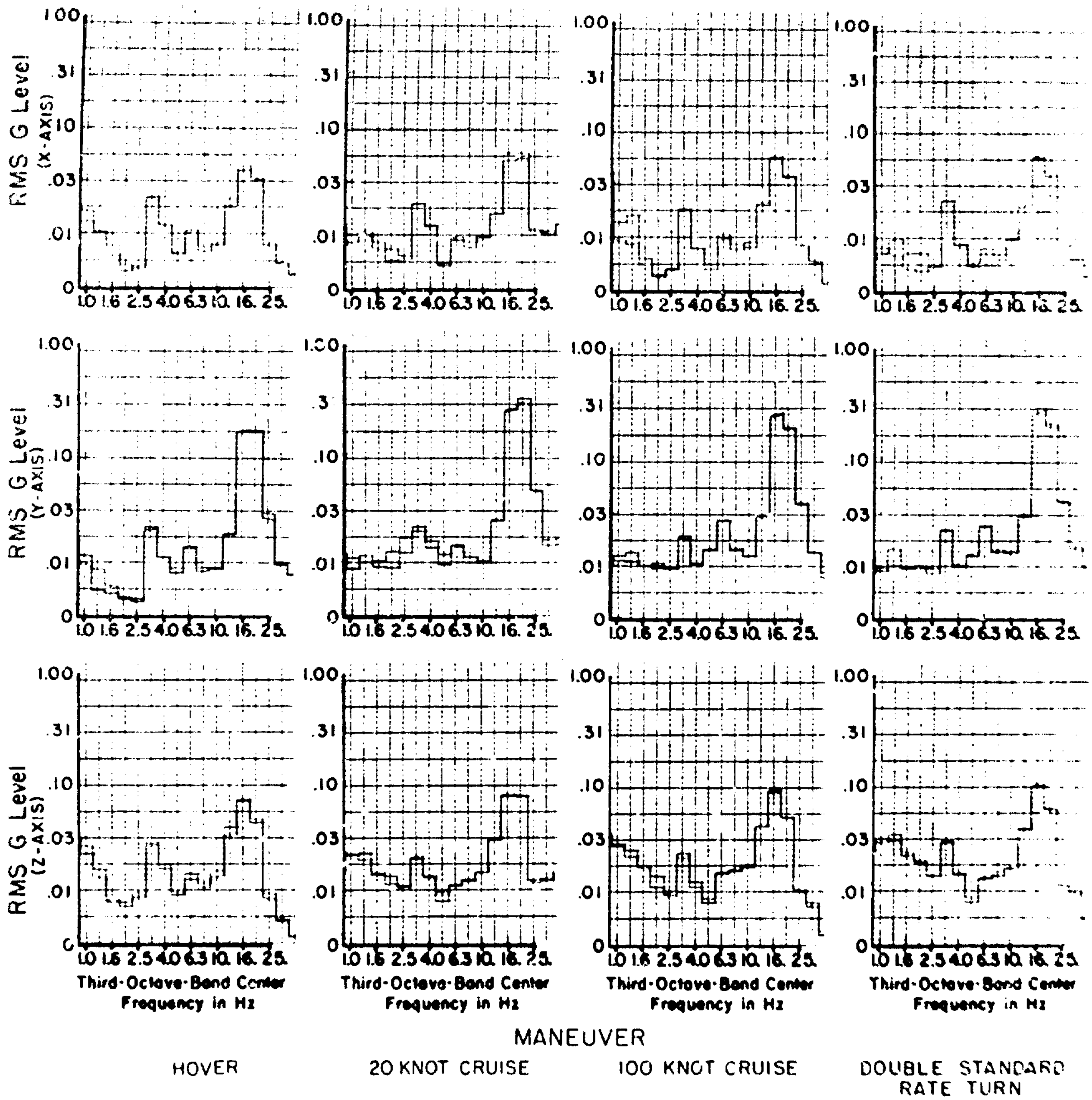
74



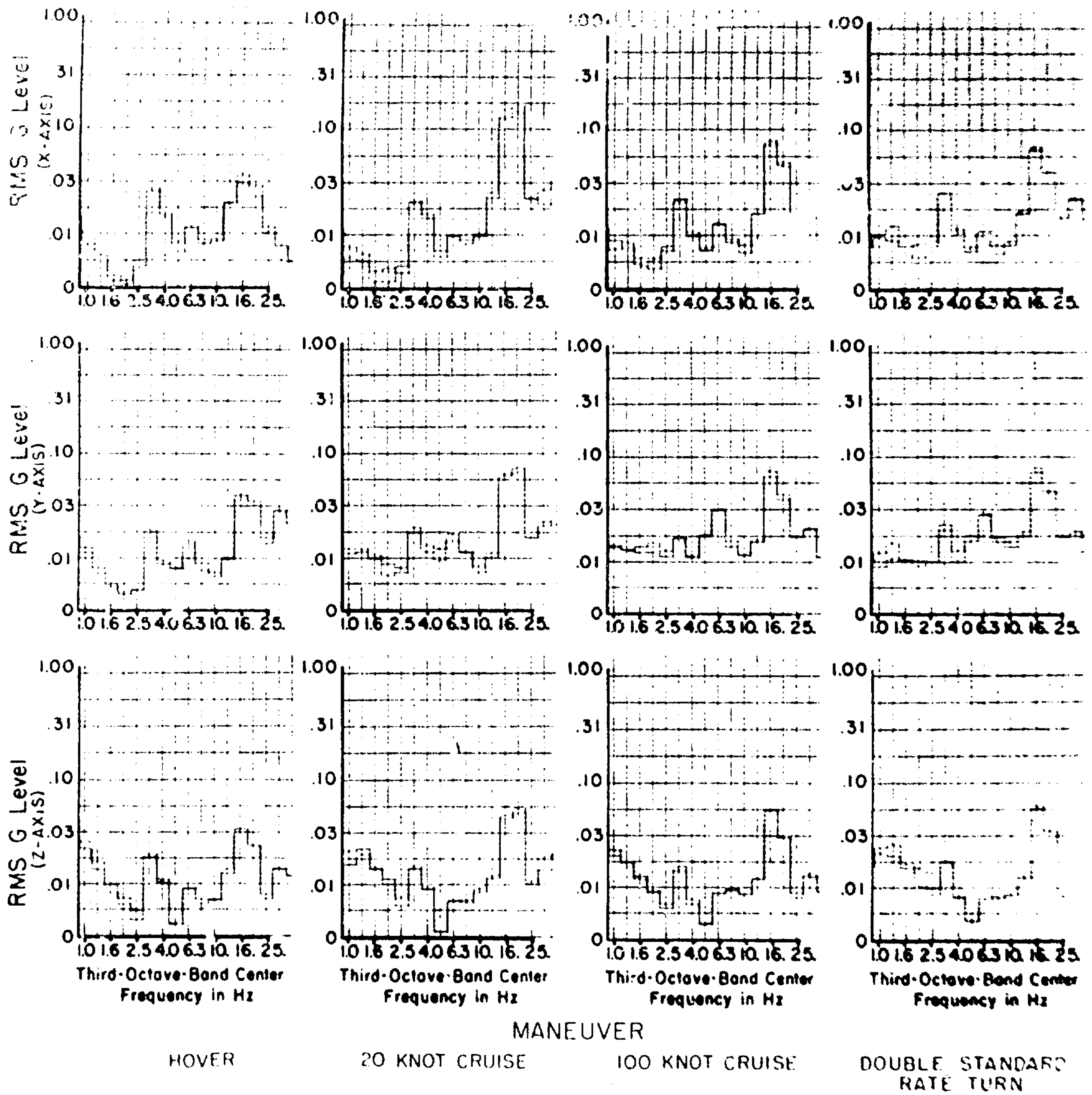
Pilot's Head CH-47C

APPENDIX C

Third Octave-Band Spectrograms for Collective and Rudder Pedal (SH-3A) Free of Pilot Contact.



Collective Control Stick SH-3A



Rudder Pedal SH-3A